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Invited review

Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework

Joel C. Gill [a,*], Bruce D. Malamud [b]

[a] Research done at Department of Geography, King's College London, Currently at British Geological Survey, Keyworth, UK
[b] Department of Geography, King's College London, UK

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ABSTRACT

This paper 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 the three groups we identify eight sub-groups: subsurface material extraction, subsurface material addition, land use change, surface material extraction, surface material addition, hydrological change, explosion, and combustion (fire). We use an existing classification of 21 natural 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. (ii) 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. (iii) Identify, through an assessment of >120 references, from both grey- and peer-review literature, 57 examples of anthropogenic processes triggering natural hazards, citing location-specific case studies for 52 of the 57 identified interactions. (iv) Examine the role of anthropogenic process types (we use as an example vegetation removal) catalysing or inadvertently impeding a given natural hazard interaction, where the impedance of natural hazard interactions does not include deliberate hazard reduction activities (e.g., engineered defences). Through (i)–(iv) 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.

Contents

* Corresponding author.
E-mail address: joell@bgs.ac.uk (J.C. Gill).

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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 paper 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 paper, introduce further context to the discussion of human influence on Earth systems, noting some initial examples, and summarise the paper's organisation.

In the context of this paper, 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' is used here, and throughout the text, 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; Duncan, 2014; Gill and Malamud, 2014; Duncan et al., 2016). In Gill and Malamud (2016) we distinguished and discussed three distinct hazard and process groups that can be considered in a multi-hazard framework: natural hazards, anthropogenic processes, and technological hazards/disasters. Here, we focus on the intra-and inter-actions within and between the first two of these groups, natural hazards and anthropogenic processes.

We now briefly discuss human influence on Earth systems. The total human population on Earth has recently exceeded 7.3 thousand million people (US Census Bureau, 2016) 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 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 involve 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., 2013; Brenning et al., 2015). Many other instances of anthropogenic processes influencing natural hazards are described in the literature, with examples referred to throughout this paper.

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. Analysing these important networks of interactions can assist in the development of holistic multi-hazard frameworks.

This paper is organised as follows: Section 2 on anthropogenic processes presents background information, describes in detail the anthropogenic processes examined here, their interactions, and possible mechanisms by which they might interact with natural hazards. Section 3 presents the results of a review to identify and visualise the triggering relationships between anthropogenic process types and natural hazards. Section 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 5, including a description of the integration of anthropogenic processes into multi-hazard frameworks. Final conclusions are noted in Section 6.

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 2.1), followed by a description of peer-review and grey literature review procedures used in both this and future sections (Section 2.2), a presentation of our final classification of anthropogenic processes considered in this study (Section 2.3), a short discussion of some of these anthropogenic processes in the context of their definition as intentional, non-malicious processes (Section 2.4), an overview, characterisation and visualisation of *anthropogenic process-anthropogenic process* interactions (Section 2.5), and a discussion of the two types of *anthropogenic process-natural hazard* interaction considered in this study (Section 2.6).

2.1. Past research on anthropogenic processes

A few broad classifications or reviews that include anthropogenic processes exist. Here we introduce two of these classifications, based on (i) artificial ground and (ii) land-use types, as examples of how some 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 Guatemalan 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.

These two examples illustrate that classifications that include anthropogenic processes do exist. We seek to build on these in later sections to develop a broader classification that can be effectively used for the assessment 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 paper, we apply our classification to an assessment of the influence of anthropogenic processes on natural hazards and natural hazard interactions.

2.2. Review methodology and database development

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

Task I. Develop a systematic classification of anthropogenic process types (Section 2.3).
Task II. Determine which anthropogenic process types interact with other anthropogenic process types (Section 2.5).
Task III. Determine which anthropogenic process types trigger natural hazards (Section 3).
Task IV. Explore ways to consider anthropogenic process types catalysing and impeding natural hazard interactions, using the example of vegetation removal (Section 4).

In our research methodology, the order in which these tasks were completed (Tasks III, I, II, then IV) differs from the order in which they appear in this paper. In this Section 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 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, Section 3) 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 1. In the context of this paper, 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.

Guiding principle ‘ii’ in Table 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 3) as initially classified and described in Gill and Malamud (2014). In Table 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 anthropogenic process types (Task I, Section 2.3). In total, the review of *anthropogenic process-natural hazard interactions* resulted in >120 references being identified and included in a database that shows the influence of anthropogenic processes in triggering natural hazards, all

Table 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 et al., 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 >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?".
(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 being taken to present the 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.

of which are noted in the Supplementary Material. 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 5.1.

This classification of anthropogenic process types and literature database then facilitated an examination of which anthropogenic process types interact with other anthropogenic process types (Task II, Section 2.5), and helped to examine the influence of vegetation removal on 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.

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 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 subsurface/surface/both, and (iii) the nature of the anthropogenic input.

Our final classification consists of 18 anthropogenic process types and is given in Table 2. The 18 process types are placed into three groups according to where (relative to the Earth's surface) the anthropogenic process types operate: *subsurface*, *surface*, *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 1–4 anthropogenic processes. Table 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.

When designing our classification of anthropogenic processes, potential overlaps between anthropogenic process types were considered. In Table 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*. Material (fluid) injection (**MFI**) has similarities to water addition (**WA**), with both involving the addition of fluids.

Each of the 18 selected anthropogenic process types given in Table 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^2 and temporal scale of days to weeks) and a societal transition from manual to machine-dominated farming (at an approximate spatial scale of 10^4–10^7 km^2 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 3.3 and 5.2.

We acknowledge that the list of 18 processes given in Table 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

Table 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. 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. Anthropogenic process types are ordered A to Z within each sub-group, except for 3.1 and 5.1, which are numbered as such to allow better comparison of process types within and between groups.

Group	Sub-Group	Anthropogenic Process Type			
		#	Name	Code	Description
I. Subsurface Process	1. Subsurface Material Extraction	1.1	Groundwater Abstraction	GA	**Removal** of ground water resources, resulting in reduction in pore pressures and changes to overall stress conditions.
I. Subsurface Process	1. Subsurface Material Extraction	1.2	Oil/Gas Extraction	OGE	**Extraction** of hydrocarbons from the sub-surface, resulting in changes to stress conditions.
I. Subsurface Process	1. Subsurface Material Extraction	1.3	Subsurface Infrastructure Construction	SC	**Extraction** of solid material from the sub-surface, due to construction (i.e.,tunnelling), resulting in changes to stress conditions.
I. Subsurface Process	1. Subsurface Material Extraction	1.4	Subsurface Mining	SM	**Extraction** of solid material from the sub-surface, resulting in changes to stress conditions.
I. Subsurface Process	2. Subsurface Material Addition	2.1	Material (Fluid) Injection	MFI	**Addition** 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	**Removal** of tree cover for commercial and industrial purposes,and urban development.
II. Surface Process	3. Land Use Change	3.2	Agricultural Practice Change	AC	**Changes** in agriculture, including machinery introduction or crop changes. Aspects associated with deforestation.
II. Surface Process	3. Land Use Change	3.3	Urbanisation	UR	Highly **landscaped** environments due to a population increase in a given area.
II. Surface Process	4. Surface Material Extraction	4.1	Infrastructure Construction (Unloading)	IC	**Removal** of mass on the land surface, through infrastructure development (e.g.,cut and excavated slopes).
II. Surface Process	4. Surface Material Extraction	4.2	Quarrying/Surface Mining (Unloading)	QSM	**Excavation** and/or **removal** of mass on the land surface (e.g., quarrying, surface mining).
II. Surface Process	5. Surface Material Addition	5.1	Infrastructure (Loading)	IN	**Addition** of mass to the land surface, through infrastructure development.
II. Surface Process	5. Surface Material Addition	5.2	Infilled (Made) Ground	IMG	Material **placement** (e.g.,mine and demolition waste, sediment) on the land surface and in surface voids to create infilled ground (e.g.,bay-fill deposits).
II. Surface Process	5. Surface Material Addition	5.3	Reservoir and Dam Construction	RD	**Construction** of reservoirs. These can result in increased surface loading and pore water pressures, along with changes to surface hydrology.
III. Subsurface & Surface Process	6. Hydrological Change	6.1	Drainage and Dewatering	DD	Artificial **lowering** of the water table through pumping or evaporation (often localised and temporary).
III. Subsurface & Surface Process	6. Hydrological Change	6.2	Water Addition	WA	Poor **removal** of water or the intentional addition of surplus water, both contributing to increases in pore water pressures and erosive capacity.
III. Subsurface & Surface Process	7. Explosion	7.1	Chemical Explosion	CE	Intentional **detonation** of conventional (non-nuclear) explosives. High energy release (heat, light, sound, and pressure).
III. Subsurface & Surface Process	7. Explosion	7.2	Nuclear Explosion	NE	Intentional **detonation** of nuclear material. Generation of destructive force by nuclear **fission** and **fusion**. Intense release of energy, high temperatures and contamination.
III. Subsurface & Surface Process	8. Combustion (Fire)	8.1	Fire	FR	Intentional-nonmalicious **ignition** offires.Can include surface (e.g., waste, agriculture) and subsurface (e.g., coal seams) material.

Table 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)	**1. Subsurface Material Extraction**	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 time frame 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., material (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., material (fluid) injection.
	6. Hydrological Change	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 maybe permanently lowered. These processes are often more localised.
Example B (fluid addition)	**2. Subsurface Material Addition**	2.1	Material (Fluid) Injection	MFI	The deliberate addition of fluids to the deep subsurface, often a thigh pressures.
	6. Hydrological Change	6.2	Water Addition	WA	Addition of water to the surface or shallow subsurface, occurring at a range of spatial scales and pressures.

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 further subdivide the 18 anthropogenic process types. 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 our classification described in Table 2 offers a comprehensive overview of human influences on many aspects of 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.

2.4. Intentional, non-malicious processes

In Section 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 2) included within our analyses in this paper 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 2 may occur either (i) unintentionally (i.e., inadvertent or accidental human activity) or (ii) as a result of an intentional but malicious act. To help define the limits of our review, the analyses in this paper focus on those incidences where anthropogenic processes are intentional and non-malicious acts, and therefore unintentional and/or malicious acts are not included. For example, when considering a 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). It is important to recognise, however, that unintentional or malicious acts may also influence the occurrence, frequency or intensity of natural hazards.

2.5. Anthropogenic process-anthropogenic process interactions (Task II)

Using the 18 anthropogenic processes described in Table 2 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 2.5.1) and a network linkage visualisation (Section 2.5.2). The implications of these interactions are then briefly discussed (Section 2.5.3).

2.5.1. 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 initiating or continuing 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 infrastructure 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*. Material (fluid) injection (**MFI**) may occur simultaneously with oil/gas extraction (**OGE**).
iii. *After*. chemical explosion (**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 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 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 (introduced in Section 2.2, and included in the Supplementary Material). For example, references used to characterise *subsurface infrastructure construction* in our database describe diverse tunnelling projects (e.g., Türkmen and Özgüzel, 2003; Hagedorn et al., 2008; Zangerl et al., 2008), and also 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 Fig. 1 we give an 18×18 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 3 groups and 8 sub-groups introduced in Table 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, 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 Fig. 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 18×18 interaction matrix given in Fig. 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, with other anthropogenic processes existing. It is also possible that interactions between the 18 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 these limitations are possible, we suggest that the consequences of a missed relationship are low. The primary purpose of the review and analysis in Fig. 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.

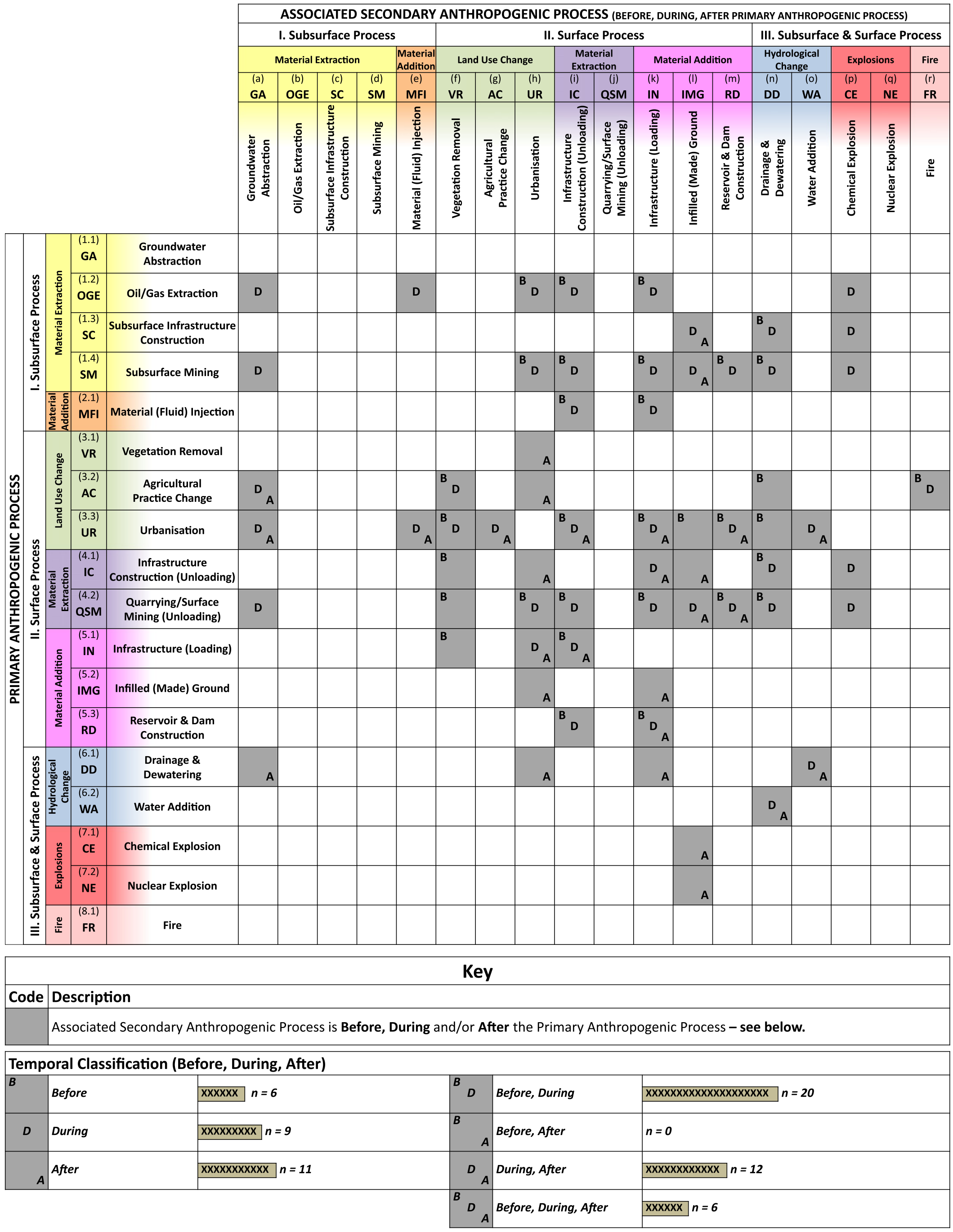


Fig. 1. *Interactions between 18 anthropogenic process types.* An 18 × 18 interaction matrix featuring the same 18 anthropogenic process types on both the horizontal axis and vertical axis. These anthropogenic process types are organised into eight sub-groups, following the same colour coding as introduced in Table 2, and placed into three broader groups. 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 insolation, but can occur in association with other anthropogenic processes.

From Fig. 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 Fig. 1) between anthropogenic process have the following summary statistics, which will be expanded and discussed in more detail in Section 2.5.2:

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, Fig. 1) have the potential to trigger one or more *associated secondary* anthropogenic process (horizontal axis). Furthermore, 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, Fig. 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 × 18 interaction matrix given in Fig. 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 Fig. 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 (in brackets is given the % of 64 *primary-associated secondary* interactions): [**B**] 32 (50%), [**D**] 47 (73%) and [**A**] 29 (45%) cases. In 26 (41%) of the 64 *primary-associated secondary* interactions, the temporal sequence is either **B** (before), **D** (during) or **A** (after). In 32 (50%) of the 64 *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 (Fig. 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.

2.5.2. Anthropogenic process linkages

In Fig. 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 visualisation tool. Network linkage diagrams, in contrast with interaction matrices, are less useful for the reader to easily extract specific hazard interaction information. Network linkage diagrams, however, use a visualisation form that is more visually striking, and therefore help the reader to appreciate the small or large number of possible interactions through the clustering of few or many lines within the visualisation. Furthermore, they allow the reader to more intuitively observe possible networks of hazard interactions cascades.

In Fig. 2, we present network linkage diagrams, with each of the 18 individual anthropogenic process types from Table 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 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: *subsurface*, *surface*, *both*. In Fig. 2, sub-groups within the same group are placed as adjoining edges. Individual octagon network linkage diagrams are also included in Fig. 2 for the three different groups introduced in Table 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 darker yellow is used to improve visibility of lines in Fig. 2A and 2B. While it is possible that one anthropogenic process may trigger further (or more intense) occurrences of itself, this is not represented in Figs. 1 and 2.

Building on the initial summary statistics presented in Section 2.5.1, 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 Fig. 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 Fig. 1.

The number of links for each of the 18 different primary anthropogenic process types included within this study were then ranked within Fig. 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 in Fig. 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.

2.5.3. Implications of anthropogenic process interactions

The results derived from Figs. 1–3 have at least two implications for the study of natural hazards, the development of multi-hazard frameworks, and disaster risk reduction (DRR). 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*

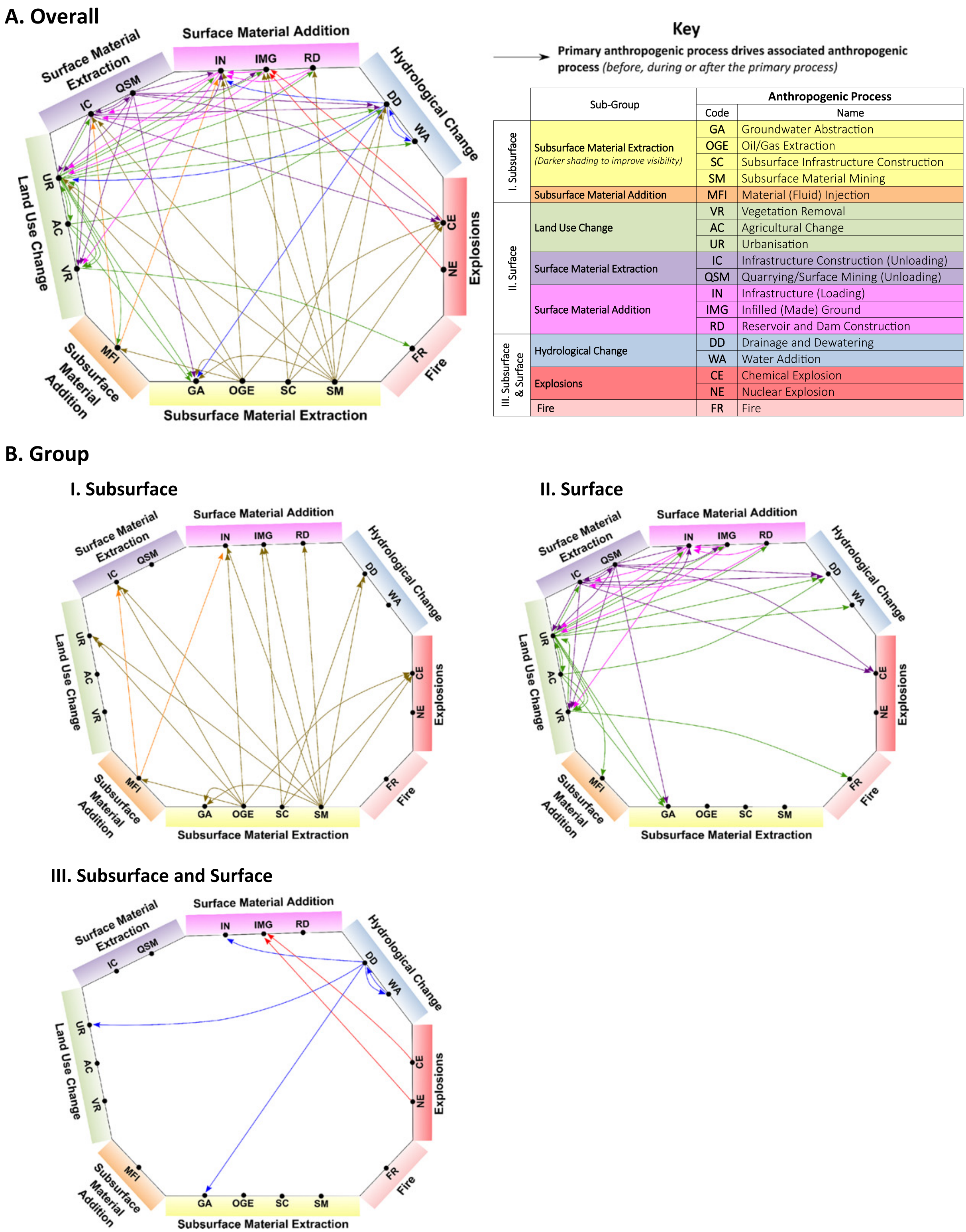


Fig. 2. *Network linkage diagrams showing interactions between 18 anthropogenic process types*, based on a design-structure presented in Gill and Malamud (2014). The principal octagon network linkage diagram (A) features 18 coded anthropogenic process types, with codes noted in the key (see also Table 2), and is an alternative visualisation of information presented in Fig. 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 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.

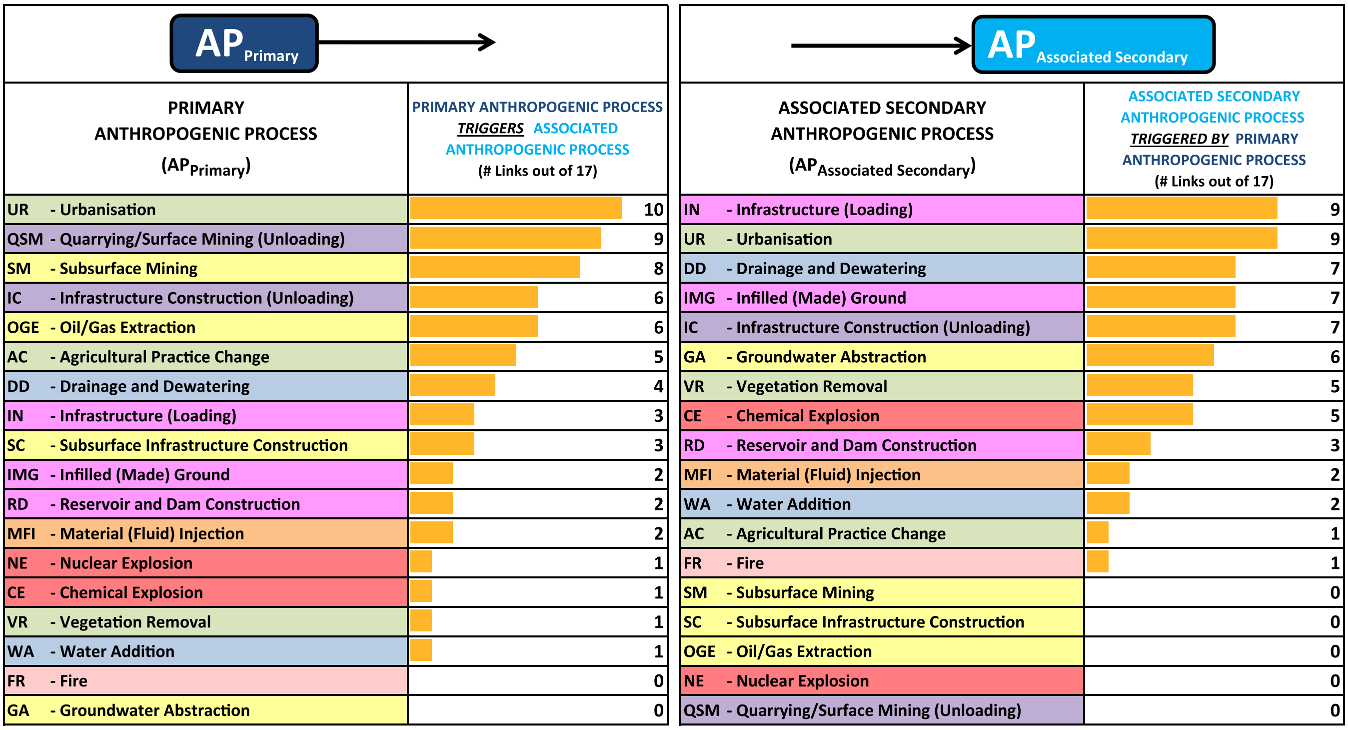


Fig. 3. *Ranking of number of links for primary anthropogenic process types* ($AP_{Primary}$) *and associated secondary anthropogenic process types* ($AP_{Associated\ Secondary}$). A quantification and ranking of anthropogenic processes according to (left) the number of links of primary anthropogenic 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 Fig. 1. In this example, the associated secondary anthropogenic process may occur before, during, and/or after the primary anthropogenic process.

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 5.2.

2.6. Anthropogenic processes and natural hazards

Having developed a classification scheme for anthropogenic processes (Task I, Section 2.3) and considered *anthropogenic process-anthropogenic process* interactions (Task II, Section 2.5), we now proceed to consider how these anthropogenic processes can influence natural hazards as background to Task III (Section 3) and Task IV (Section 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. Fig. 4 summarises and visualises these two interaction types, which we now discuss in turn.

Anthropogenic Triggering (Fig. 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 road cuttings, 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 3.

Anthropogenic catalysis/impedance (Fig. 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 Fig. 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, so as to catalyse the interaction. We change notation here from **B** (before), **D** (during), **A** (after) used in Fig. 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. 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 Fig. 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_1', t_2', t_3' and t_1'', t_2'', t_3'). Anthropogenic catalysis and impedance are further discussed in Section 4.

3. Anthropogenic triggering of natural hazards (Task III)

Using the classification of anthropogenic processes developed in Section 2.3, we now consider which of these 18 anthropogenic processes can trigger different natural hazards. This section begins by introducing the 21 natural hazards that we will consider in this study (Section 3.1), before proceeding to describe our overview, characterisation and visualisation of *anthropogenic process-natural hazard* triggering interaction relationships (Section 3.2), and analysing *anthropogenic process-natural hazard* type linkages (Section 3.3).

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), *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 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 subclasses, such as mudslide, debris flow, rockfalls and rotational slides. The proposed and utilised classification of natural hazards 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.

3.2. Anthropogenic process-natural hazard triggering interactions

We now examine potential triggering interactions between the 18 anthropogenic process types (described in Table 2) and the 21 natural hazard types (described in Table 4). Using the review procedure outlined in Section 2.2, our 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 >120 references, listed in full in Table S1 of the Supplementary Material, with some of these also cited in this paper.

In our methodology, each of the possible 378 *anthropogenic process-natural hazard* triggering interactions were considered using large literature search databases (Google Scholar, Web of Science) to search for relevant (but not all) case studies and literature. 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

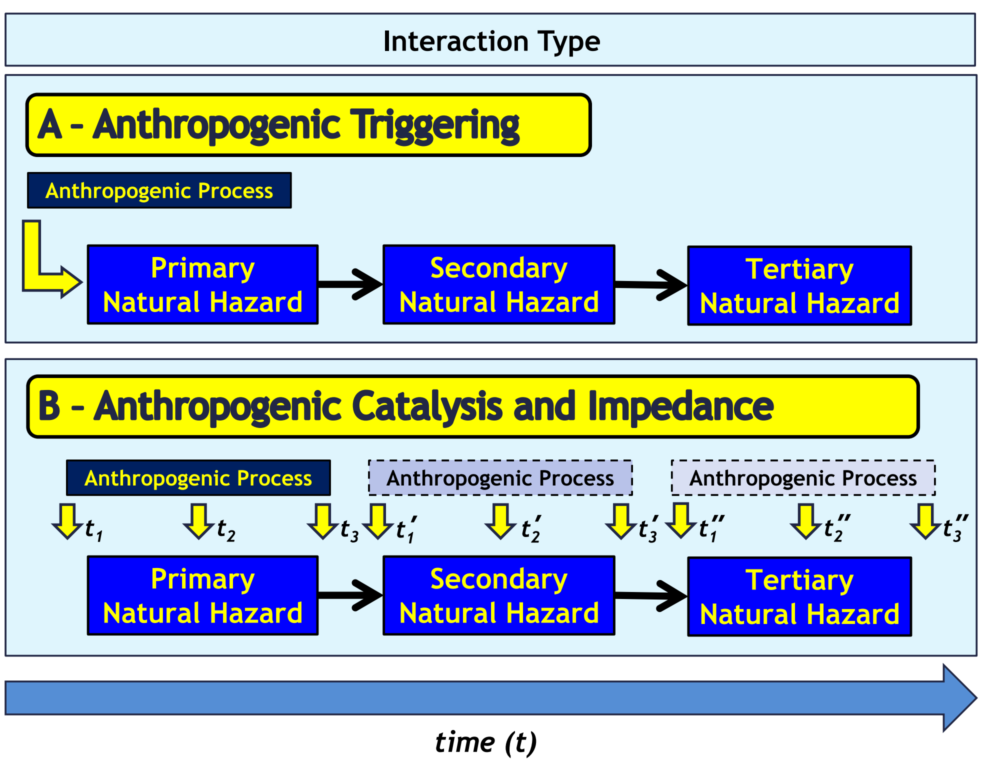


Fig. 4. *Mechanisms relating anthropogenic process types to natural hazards and natural hazard interactions.* Two mechanisms are presented by which anthropogenic processes, such as those outlined in Table 2, may relate to natural hazards, such as those outlined in Table 4. The first mechanism (**A**) 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″).

Table 4
Natural hazard groups and natural hazard types used in this paper. An outline of 6 hazard groups, containing 21 different natural hazard types, with the codes used in this paper and component hazards noted (adapted from Gill and Malamud, 2014).

Natural Hazard			Component Hazards *(where applicable)*
Group	Type	Code	
Geophysical	Earthquake	**EQ**	Ground Shaking, Ground Rupture, 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 Soil-Creep
	Snow Avalanche	**AV**	
Hydrological	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
Shallow Earth Processes (adapted from Hunt, 2005)	Regional Subsidence	**RS**	Tectonic Subsidence.
	Ground Collapse	**GC**	Karst and Evaporite Collapse, Piping, Metastable Soils
	Soil (Local) Subsidence	**SS**	Soil Shrinkage, Natural Consolidation Settlement
	Ground Heave	**GH**	Tectonic Uplift, Expansion (Swelling) of Soils and Rocks
Atmospheric	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
Biophysical	Wildfire	**WF**	
Space/Celestial	Geomagnetic Storm	**GS**	
	Impact Event	**IM**	Asteroid, Meteorite

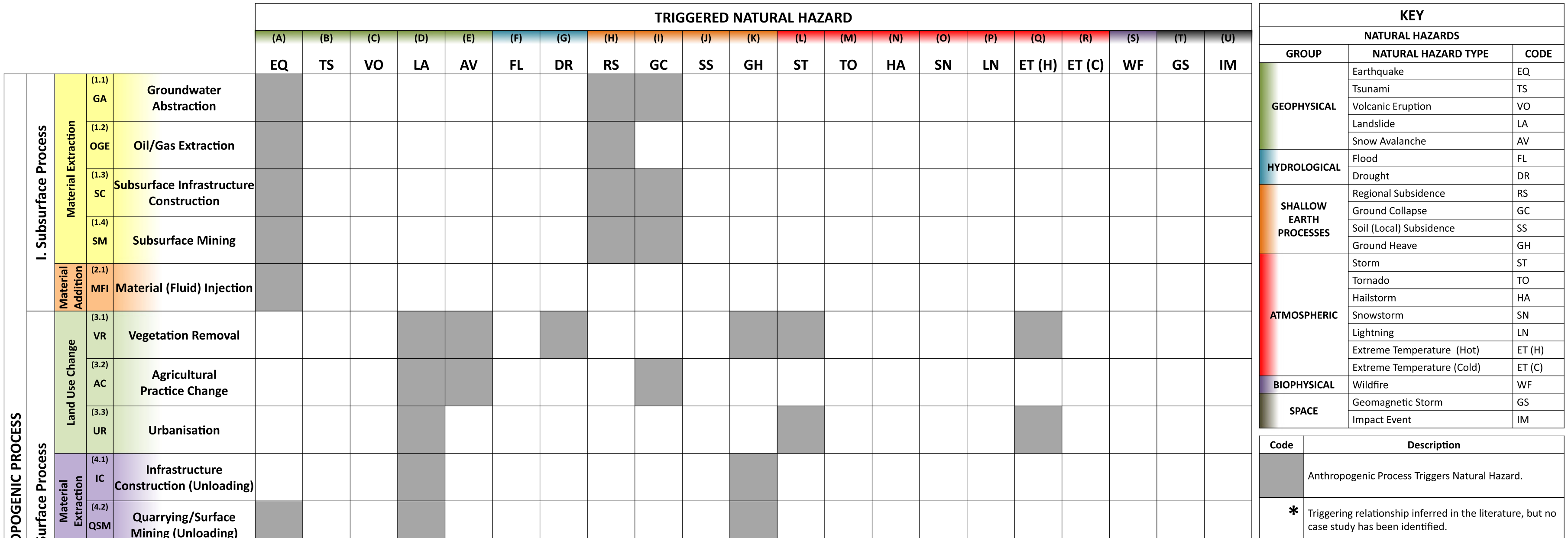
anthropogenic process and each natural hazard. For example, in addition to 'earthquake', other search terms included 'tremor'. 'Seismic activity', and 'seismic shaking'. Articles returned were briefly reviewed to determine their relevance, and whether it supported the existence of a particular interaction. Articles mentioning a natural hazard and an anthropogenic process but not considering the relationship between these were rejected. Articles that did discuss a relationship between an anthropogenic process and a natural hazard were 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 Fig. 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 whereby an anthropogenic process type may trigger a natural hazard. The anthropogenic processes in Fig. 5 are arranged into three groups and further divided into eight sub-groups, as described in Section 2.3 and Table 2. Natural hazards are organised into six hazard groups and coded, as introduced in Section 3.1 and Table 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 Fig. 5, a case study (with spatial and temporal limits) was found in the examined literature. This collection of case studies is also noted in the Supplementary Material Table S1. For example, a nuclear explosion may trigger a landslide or rock avalanche (Fig. 5, cell 7.2D) 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 Fig. 5), but a relationship is described or conjectured in the literature. For example, a nuclear explosion may trigger a snow avalanche (Fig. 5, cell 7.2E), but a clearly defined case study was not identified in the literature. While we note specific case studies for 52 of the 57 *anthropogenic process–natural hazard* triggering interactions in Supplementary Material Table S1, 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.

Fig. 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 Fig. 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



Footnotes

[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.
[General #2] – Where earthquakes are noted to be triggered, these may be low magnitude, low intensity events (colloquially referred to as 'earth tremors').
[1.3A, 1.4A] – Primarily through rock-bursts, as lateral pressures are removed.
[3.1L] – Vegetation removal is both noted to increase and decrease precipitation/rainfall, through changes in evaporation and cloud formation. Differences relate to altitude and topography.
[5.3L] – Some studies suggest both increases and decreases in the amount of rainfall (at different times of the year). There is disagreement in the literature about the nature of this relationship.
[5.3R] – 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 .
[7.1B] – No case study identified in literature, but some literature to support the existence of this relationship.
[7.1D] – Blasting increases the likelihood of slope failure through a deterioration of rock mass quality.
[7.1S] – Case study infers blasting as a possible initiation of forest fire, but cause is unclear.
[7.2B, 7.2E, 7.2S] – No case studies identified in literature, due to relatively few nuclear explosions. Literature to support these relationships does exist.

Fig. 5. *Identification of anthropogenic process–natural hazard triggering interactions.* An 18 × 21 interaction matrix with selected anthropogenic processes on the vertical axis and selected natural hazards on the horizontal axis. Anthropogenic processes (described in Table 2) are organised into 3 groups and further classified into 8 general sub-groups of anthropogenic processes. Natural hazard types (described in Table 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 the **Supplementary Material**. 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.

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 Fig. 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 then 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 Fig. 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 Fig. 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 relate 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.

3.3. Anthropogenic process-natural hazard type linkages

Using the 57 *anthropogenic process–natural hazard* triggering interactions presented in Fig. 5, we can apply the same ranking method used previously in Section 2.5.2 and Fig. 3, to analyse the relative severity of each *triggering anthropogenic process* and *triggered natural hazard* in the context of this study. In Fig. 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 Fig. 6 we use the term *anthropogenic process to natural hazard* links). Each of the 18 anthropogenic processes can trigger a maximum possible of 21 natural hazards.

ii. *Triggered natural hazard (NH)*. The extent to which each natural hazard is triggered by anthropogenic processes (in Fig. 6 we use the term *natural hazard from anthropogenic process* links). Each of the 21 natural hazards can be triggered by a maximum possible of 18 anthropogenic processes.

For each triggering anthropogenic process (AP) and triggered natural hazard (NH) in Fig. 6, we sum the total number of relevant linkages from Fig. 5, ranking them from highest to lowest number of links, and present the information in Fig. 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 Fig. 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 together 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 highest three 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 lowest three 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 (≥50%) percentages, relating to landslides, earthquakes and ground collapse.

The information and rankings in Fig. 6 do not reflect the overall likelihood of any particular anthropogenic process or triggering relationship. Certain anthropogenic processes ranking high (left hand side of Fig. 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 Fig. 6) may also have received that ranking through the

TRIGGERING ANTHROPOGENIC PROCESS (AP)	ANTHROPOGENIC PROCESS TO NATURAL HAZARD LINKS (Number of Links)	ANTHROPOGENIC PROCESS TO NATURAL HAZARD LINKS (% of Max. 21 Links)
VR - Vegetation Removal	6	29%
NE - Nuclear Explosion	6	29%
CE - Chemical Explosion	6	29%
RD - Reservoir and Dam Construction	5	24%
WA - Water Addition	4	19%
UR - Urbanisation	3	14%
AC - Agricultural Practice Change	3	14%
GA - Groundwater Abstraction	3	14%
SM - Subsurface Mining	3	14%
QSM - Quarrying/Surface Mining (Unloading)	3	14%
SC - Subsurface Infrastructure Construction	3	14%
IN - Infrastructure (Loading)	3	14%
OGE - Oil/Gas Extraction	2	10%
DD - Drainage and Dewatering	2	10%
IC - Infrastructure Construction (Unloading)	2	10%
MFI - Material (Fluid) Injection	1	5%
IMG - Infilled (Made) Ground	1	5%
FR - Fire	1	5%

TRIGGERED NATURAL HAZARD (NH)	NATURAL HAZARD FROM ANTHROPOGENIC PROCESS LINKS (Number of Links)	NATURAL HAZARD FROM ANTHROPOGENIC PROCESS LINKS (% of Max. 18 Links)
LA - Landslide	11	61%
EQ - Earthquake	9	50%
GC - Ground Collapse	9	50%
AV - Avalanche	4	22%
GH - Ground Heave	4	22%
RS - Regional Subsidence	4	22%
WF - Wildfire	3	17%
ST - Storm	3	17%
FL - Flood	2	11%
ET(H) - Extreme Temperature (Heat)	2	11%
SS - Soil (Local) Subsidence	2	11%
TS - Tsunami	2	11%
ET (C) - Extreme Temperature (Cold)	1	6%
DR - Drought	1	6%
VO - Volcanic Eruption	0	0%
LN - Lightning	0	0%
TO - Tornado	0	0%
HA - Hailstorm	0	0%
SN - Snowstorm	0	0%
IM - Impact Event	0	0%
GS - Geomagnetic Storm	0	0%

Fig. 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 (Fig. 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 Fig. 5.

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 Fig. 5, differential intensities are also not reflected in the rankings of Fig. 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*. Region-specific likelihood, intensity and impact data could refine the rankings within Fig. 6 to better support planning and mitigation activities.

4. Anthropogenic catalysing and impedance of natural hazard interactions (Task IV)

Anthropogenic processes can catalyse or impede natural hazard interactions, as introduced in Section 2.6. Here in Task IV (see Section 2.2 for description of Tasks I to 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).

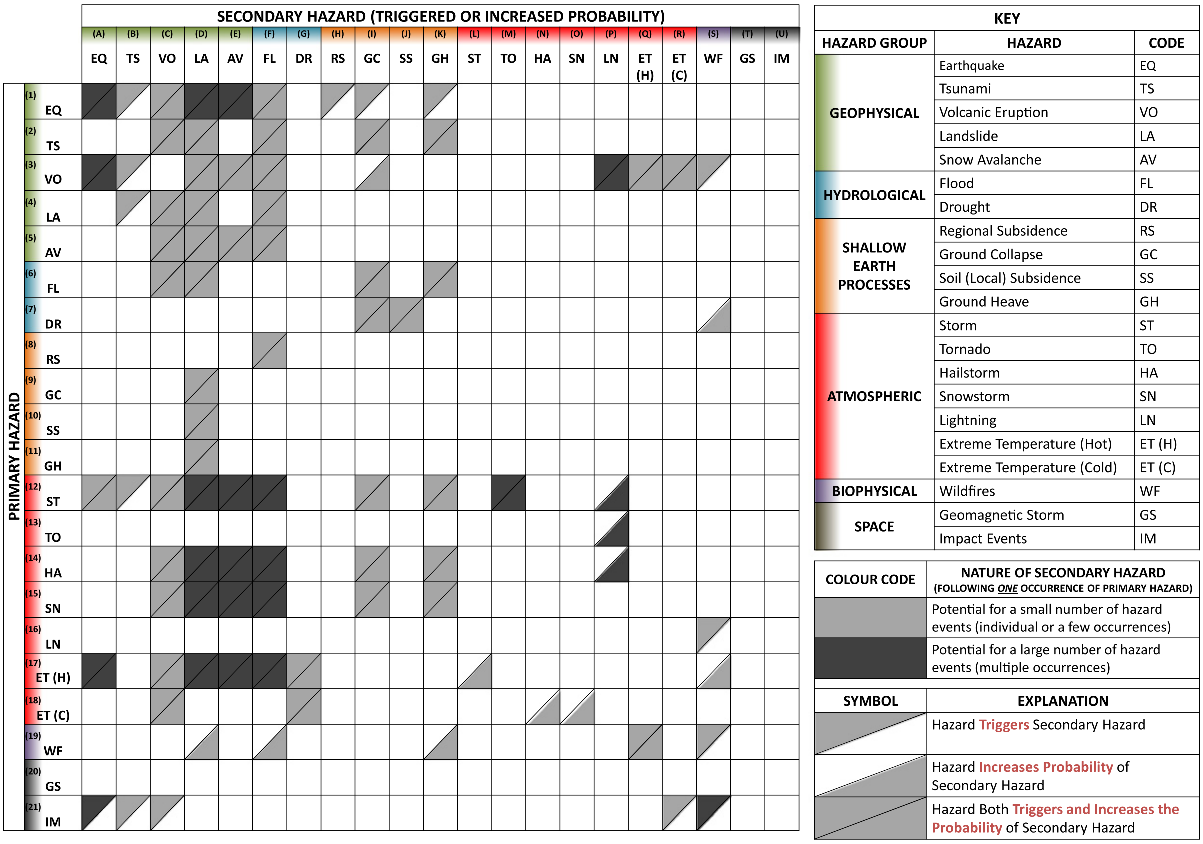
4.1. Natural hazard interactions

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 and using a 21 × 21 interaction matrix identified 90 possible triggering and increased probability interactions (out of 21 × 21 = 441 possible interactions). This interaction matrix is presented in Fig. 7 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 >200 references from peer-reviewed and grey literature. Identified natural hazard interactions differ 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*. 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*. 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* and *increased probability* 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.



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.

Fig. 7. *Identification of hazard interactions* (*from* Gill and Malamud, 2014). A 21 × 21 interaction 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 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. 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 classified into six hazard groups: 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.

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).

4.2. Visualising anthropogenic process types catalysing or impeding natural hazard interactions

As previously illustrated in Fig. 4B and discussed in Section 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 2 and the 90 natural hazard interactions shown in Fig. 7, giving 18 × 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 Fig. 5 (Section 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 × 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 <90 and relevant anthropogenic process types <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 Fig. 7 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^2 field for agriculture) or over a larger spatial extent (e.g., a 100 km^2 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 Fig. 7.

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 Fig. 7. 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) was used to support this process, supplemented by a combination of expert judgement and relevant literature to determine if vegetation removal could catalyse or impede each mechanism (and therefore the interaction). The literature used to support Task IV included some of the references included in the database introduced in Section 2.2 (and included in the Supplementary Material), 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**, Fig. 7, row 12) and a flood (**FL**, Fig. 7, 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) that we identified using a Boolean search of the anthropogenic process type, primary natural hazard and secondary natural hazard. Additional information could be included in the matrix (e.g., coding cells according to whether they are populated using literature, expert knowledge, or a combination of both), although this additional variable may add too much complexity to the matrix.

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 Fig. 8 we present these interactions using an adapted interaction matrix. As in Fig. 7, 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 Fig. 8 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. We also do not represent the sources of information used to populate cells within this matrix. Given the many parameters already included in Fig. 8, this additional variable is omitted in order to present a simpler, more understandable matrix.

In Fig. 8, 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 the following interactions:

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 Fig. 8, shown using pink shading and labelled '**I**'. Examples include vegetation removal impeding the following interactions:

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. *Drought increasing the probability of wildfires*, through the removal of available biofuel. This interaction might be less likely to occur (i.e., the interaction will be impeded) if drought results in vegetation removal, and therefore increases the development of areas with little or no vegetation, with those areas preventing the spread and growth of wildfires.

In this section, we have given an example of one anthropogenic process (vegetation removal) selected from Section 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.

5. Discussion

Within this study we have assessed, classified, and visualised the potential of 18 anthropogenic processes to trigger other anthropogenic processes (Section 2), and 21 natural hazards (Section 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). 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 Table S1 of the Supplementary Material.

In this discussion section we describe some of the limitations and uncertainties associated with our analysis and visualisations (Section 5.1), discuss the integration of this research into multi-hazard frameworks, including a description of ways that visualisations from Sections 2 to 4 can be combined and used to strengthen multi-hazard frameworks (Section 5.2), and discuss how interaction frameworks

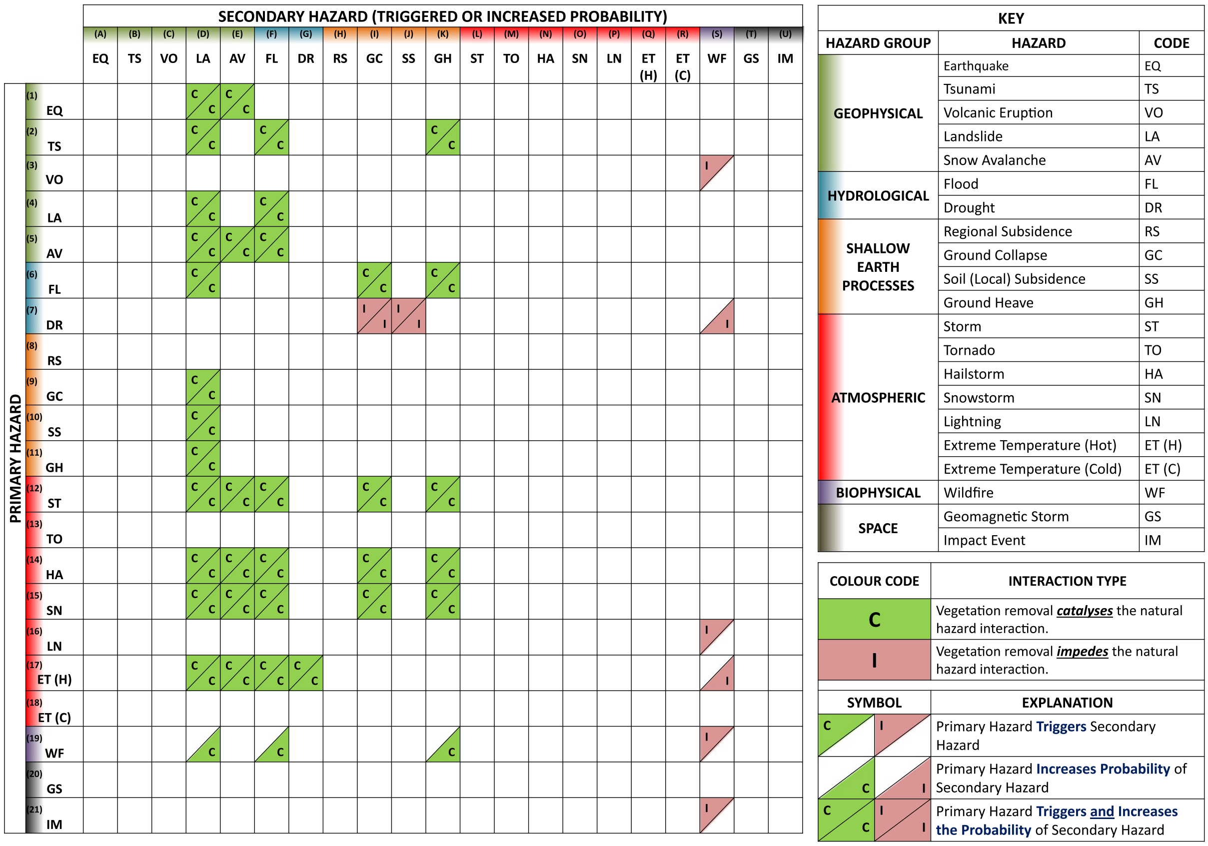


Fig. 8. *Influence of vegetation removal on natural hazard interactions.* A 21 × 21 interaction matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis. These hazards are coded and classified as explained in the key and Table 4. This interaction matrix shows cases 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**'.

incorporating anthropogenic processes can be used within DRR (Section 5.3).

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 paper 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 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 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), although we recognise they may influence other forms of environmental degradation.

iii. *Scale of interest.* We introduced in Section 2.3 the importance of spatial and temporal scale of anthropogenic processes. Most of the processes included within Table 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^2) 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^2 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 2 to 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 2.2 and 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 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 then 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 paper 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.
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.

5.2. Integration of anthropogenic processes into multi-hazard frameworks

In this paper we have suggested that anthropogenic processes have a significant influence on the triggering of natural hazards (Section 3) and catalysing/impeding of natural hazard interactions (Section 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 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 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 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 Figs. 1, 5, 7 and 8 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 paper facilitates a more enhanced and comprehensive assessment of potential interactions for multi-hazard frameworks. Fig. 9 shows how a combination of Figs. 5 and 7 can be used to support a visualisation of networks of hazard interactions (cascades). Fig. 9 combines the 18×21 interaction matrix of *anthropogenic process types triggering natural hazards* (Fig. 5) with the 21×21 interaction matrix of *natural hazards triggering natural hazards* (Fig. 7), 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.

In a further example, Fig. 10 combines the 18×18 interaction matrix of *anthropogenic interactions* (Fig. 1) with the 18×21 interaction matrix of *anthropogenic process types triggering natural hazards* (Fig. 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 **Fig. 10** 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 Fig. 10, for example, that three of the four anthropogenic process types could independently trigger

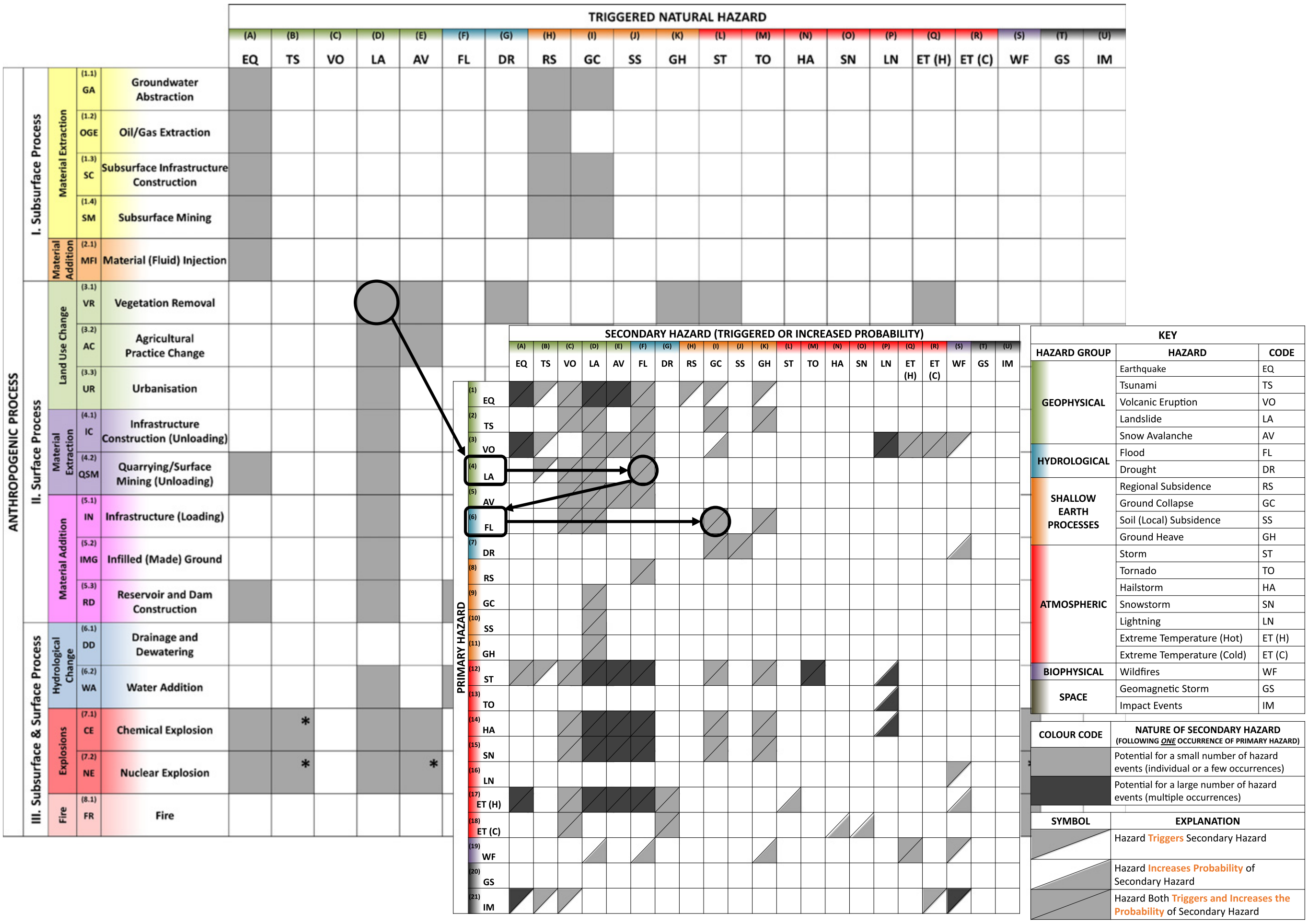


Fig. 9. *Initiation of network of interactions (cascade) visualised by combining* Figs. 5 and 7. A figure combining the 18 × 21 interaction matrix of anthropogenic process types triggering natural hazards (Fig. 5) with the 21 × 21 interaction matrix of natural hazards triggering natural hazards (Fig. 7). 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**).

ground collapse (**GC**). The concurrent or simultaneous occurrence of these three anthropogenic processes could result in greater susceptibility to ground collapse.

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 (Figs. 1, 5, 7, 8) can also be overlain as described previously (Figs. 9 and 10).
ii. *Network linkage diagrams.* This visualisation format (used in Fig. 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.

5.3. Multi-hazard frameworks for disaster risk reduction (DRR)

Principal user communities for the visualisations derived within this paper 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 Disaster Risk Reduction 2015–2030 (UNISDR, 2015). We suggest that the different types of

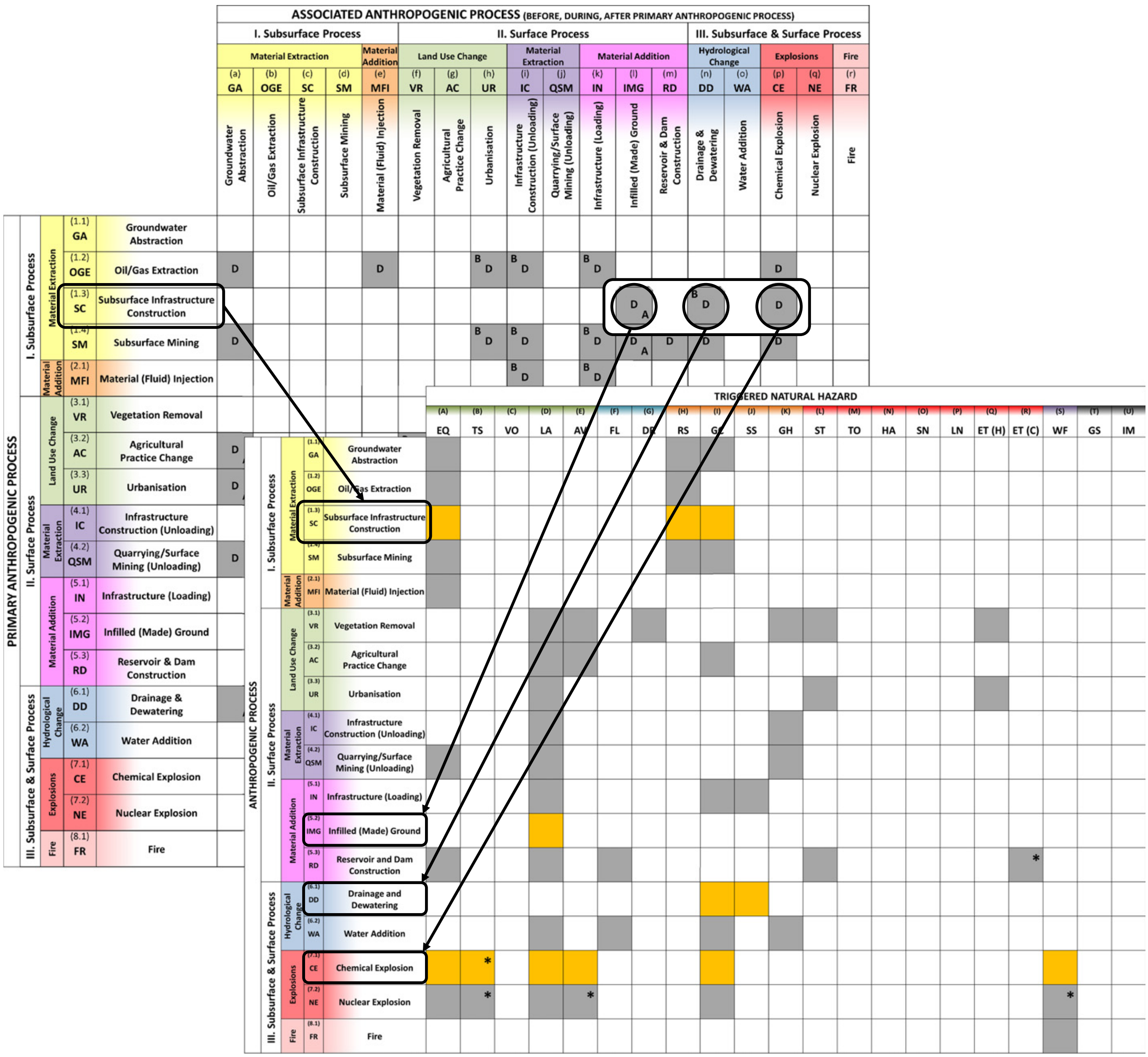


Fig. 10. *Triggering of natural hazards by an ensemble of anthropogenic processes, visualised by combining* Figs. 1 and 5. A figure combining the 18 × 18 interaction matrix of anthropogenic process type interactions, with interactions indicated using grey cell shading (Fig. 1) with the 18 × 21 interaction matrix of anthropogenic process types triggering natural hazards, with interactions indicated using grey and orange cell shading (Fig. 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.

interaction matrix visualisations that we have developed (Figs. 1, 5, 7, 8, 9 and 10) can help to support the development of integrated policies towards DRR and holistic disaster risk management:

i. *Anthropogenic process interactions* (Fig. 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 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 (Fig. 10).

ii. *Anthropogenic process–natural hazard triggering interaction relationships* (Fig. 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 Fig. 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* (Fig. 8). 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 Fig. 8 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* (Figs. 9 and 10). In Figs. 9 and 10 we use combinations of Figs. 1, 5 and 7 to better characterise and visualise networks of hazard interactions (cascades). The first example (Fig. 9) used Figs. 5 and 7 to show how an anthropogenic process type can initiate a network of interacting hazards (cascades). The second example (Fig. 10) used Figs. 1 and 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; Marzocchi et al., 2012; Neri et al., 2013; 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.

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 > 120 references (Supplementary Material Table S1) 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 2 to 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.

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Appendix A. Supplementary Material

Supplementary references, figures and tables to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2017.01.002. This includes one table, five figures, and 125 references used within this work.

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