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Discussions

A methodology to compile multi-hazard interrelationships in a data-scarce setting: an application to Kathmandu Valley, Nepal

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Abstract. This paper introduces a multifaceted methodology to identify and compile single natural hazards and multi-hazard interrelationships within the context of data-scarce urban settings, exemplified by Kathmandu Valley, Nepal. This approach integrates (i) five blended types of evidence to support a more nuanced and holistic understanding of a hazardscape where data are scarce and (ii) a 2-hour stakeholder workshop with seven participants to provide greater context to the hazards, consider their impacts through the co-production of multi-hazard interrelationship scenarios, and how this methodology could support more people-centred disaster risk reduction (DRR) strategies. We use blended evidence types, including academic literature, grey literature, media, databases, and social media, to systematically search for exemplars of single hazards and multi-hazard interrelationships that have influenced or could potentially influence Kathmandu Valley. We collated 58 sources of evidence for single hazards and 21 sources of evidence for multi-hazard interrelationships. Using these sources, our study identified 21 single hazard types across six hazard groups (geophysical, hydrological, shallow Earth processes, atmospheric, biophysical, and space/celestial hazards) and 83 multi-hazard interrelationships (12 that have direct case study evidence of previous influence in Kathmandu Valley) that might influence Kathmandu Valley. These exemplars are collated into two databases that accompany this paper. We supplement these exemplars with multi-hazard interrelationship scenarios and multi-hazard impacts developed by stakeholders engaged in DRR research and practice in Kathmandu Valley. The results illustrate the complexity of the hazard landscape, with many single hazards and multi-hazard interrelationships potentially influencing Kathmandu Valley. The research emphasises the importance of inclusive DRR strategies that recognise disaggregated impacts experienced by different social groups. This knowledge can inform the development of dynamic risk scenarios in planning and civil protection, thus strengthening multi-hazard approaches to DRR in "Global South" urban areas such as Kathmandu Valley.

1 Introduction

This paper introduces a multifaceted methodology designed to identify and compile single hazards and multi-hazard interrelationships in data-scarce urban areas in the “Global South”, setting out a rationale and approach to identifying and using exemplars of multi-hazard events to characterise the hazard landscape. In this introduction, we (i) present the challenges in characterising single hazards and multi-hazard interrelationships in data scarce urban areas, (ii) describe the methodology developed in this study and (iii) introduce Kathmandu Valley, Nepal, as the setting to which we apply our methodology.

Studies of natural hazards often focus on single, discrete hazards, such as earthquakes, floods, and storms, with more limited knowledge of multi-hazard interrelationships and their impacts (Gill et al., 2020; De Angeli et al., 2022; Ward et al., 2022). Examples of multi-hazard interrelationships include an earthquake triggering a landslide, which may block a river and trigger flooding downstream, or drought increasing the probability of wildfire. Single hazard events are often well documented in the literature (e.g., Nehren et al., 2013; The World Bank Group and the Asian Development Bank, 2021) and international databases such as EM-DAT (CRED, 2023) and DesInventar Sendai (UNDRR and LA RED, 2023), particularly concerning events with large magnitudes or where impacts turn into disasters. Databases detailing the breadth of single hazards in particular regions are generally rarer in the “Global South”, yet localised perspectives on multiple single hazards are improving (GFDRR, 2021; GFDRR Innovation Lab, 2021). Conversely, the systematic knowledge of multi-hazard interrelationships in individual regions or urban areas, and their impacts, is still limited, particularly concerning further characterisation and quantification of these interrelationships using a universal framework (Tilloy et al., 2019; Gill et al., 2020; Ward et al., 2022; Hochrainer-Stigler et al., 2023). **Table 1** summarises six systematic studies compiling multi-hazard interrelationships on a regional scale, including the systematic methodologies used and the region to which the methodology is applied. The methodologies vary from critical literature reviews to multi-hazard risk analyses as tools to gather information about multi-hazard interrelationships across geographical regions. **Table 1** situates the methodology we describe in this paper in the broader context of six systematic studies that collate multi-hazard interrelationships on a regional scale.

Table 1: Summary of six systematic studies compiling multi-hazard interrelationships on a regional scale.

Publication name	**Systematic methodologies**	**Region methodology is applied to**
A multi-hazard framework for spatial-temporal impact analysis (De Angeli et al., 2022)	Critical literature review and stakeholder workshops. The methodology considered types of multi-hazard interrelationships, impacts and stakeholder perspectives to develop a multi-hazard impact framework.	Po Valley, Italy
Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment (Liu et al., 2016)	Given different potential multi-hazard interrelationship types, the probability and magnitude of multi-hazards occurring together were calculated using hazard interaction analysis.	Yangtze river delta, China
Spatial pattern of hazards and hazard interactions in Europe (Tarvainen et al., 2006)	A causal correlation was used to identify multi-hazard interactions and select those which exceeded average hazard intensities for a given region.	Europe
Construction of regional multi-hazard interaction frameworks, with an application to Guatemala (Gill et al., 2020)	Comprehensive, systematic, and evidenced regional interaction framework populated using internationally accessible literature, locally accessible civil-protection bulletins, field observations, stakeholder interviews and a stakeholder workshop.	Guatemala
From Single- to Multi-Hazard Risk Analyses: a concept addressing emerging challenges (Kappes et al., 2010)	Multi-hazard interactions were identified using a matrix, modelled, and incorporated into a multi-hazard risk analysis.	Barcelonnette Basin, French Alps
A theoretical model for cascading effects analyses (Zuccaro et al., 2018)	Development of a cascading effects scenario analysis model, incorporating exposure data and hazard and impact models. This scenario analysis was applied to a hypothetical hazard cascade of an eruption of Nea Kameni Volcano, Santorini, Greece.	Santorini, Greece

In the past decade, the natural hazard community has evolved towards a more nuanced understanding of multi-hazards, defined as (UNDRR, 2017) the *"(1) selection of multiple major hazards that the country faces, and (2) specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects"*. There has been increasing awareness of the importance of considering multi-hazards since its inclusion in the Sendai Framework for Disaster Risk Reduction (DRR) 2015-30 (UNDRR, 2015) and implementation of the UNDRR (2017) definition. Multi-hazard approaches to DRR are an integral part of the vision and research objectives of the Sendai Framework. In Nepal, the focus of this paper, decision-makers and multi-hazard researchers have expressed the need to better integrate multi-hazard approaches into DRR strategies (Government of Nepal, 2018; Gautam et al., 2021). However, practical adoption is much more challenging (Aksha et al., 2020). Single hazard events in Nepal are documented in open-access databases such as the Nepal DRR Portal, BIPAD (Building Information Platform Against Disasters) portal (Youth Innovation Lab, 2020b), EM-DAT (CRED, 2024) and DesInventar Sendai (UNDRR & LA RED, 2024). It would be

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beneficial to have a standardised framework for collecting and recording multi-hazard event data (Youth Innovation Lab, 2020b).

A political declaration at the midterm review of the Sendai Framework noted, in Article 8, the increasingly complex nature of disaster risk, considering interrelated impacts across regions and sectors (UNDRR, 2023) and, in Article 20, called for improved collection and analysis of hazard, disaster event and impact data, specifically disaggregated data by social group, e.g., “income, sex, age and disability” (UNDRR, 2023). The scarcity of multi-hazard event and impact data in some “Global South” urban areas presents a significant challenge to risk-sensitive DRR strategies (Paudyal et al., 2015; Aksha et al., 2020). Within the context of these urban areas, where the interaction of exposure to multiple hazards and high vulnerability combine to exacerbate risk (Hallegatte et al., 2020; Shrestha et al., 2020), mapping of multi-hazard interrelationships can inform effective and people-centred DRR strategies (Scolobig et al., 2015; UNDRR, 2023). Considering these challenges, the DRR community has identified the need for a greater breadth and depth of (multi-)hazard data from diverse sources as a critical priority in better understanding hazardscapes and their impacts (Gill et al., 2021b; Šakić Trogrlić et al., 2022; Šakić Trogrlić et al., 2024). This paper applies a single-hazard and multi-hazard interrelationship scoping methodology using blended evidence types in the context of Kathmandu Valley, Nepal, as an example of a multi-hazard, data-scarce urban setting.

The global population in urban areas as of 2022 is estimated to be 4.2 billion people, with the most rapid growth in informal settlements being in low- to middle-income countries with lower adaptive capacity (Dodman et al., 2022). Within these countries, Nepal experiences high exposure to multi-hazards coupled with challenges presented by its medium Human Development Index (HDI) of 0.602 in 2021 – on a scale of 143 out of 191 countries globally – (CEDLAS and World Bank, 2022), and estimated global Multidimensional Poverty Index (MPI) of 0.074 based on a 2019 survey – compared to an estimated MPI of 0.091 for the South Asia region based on surveys between 2011 and 2022 (Alkire et al., 2023). One of the significant challenges facing urban areas in Nepal is the scarcity of hazard impact data, which is a barrier to effective DRR strategies (Chatterjee et al., 2015; SIAS, 2016). For example, within the Nepal DRR Portal, one of Nepal’s primary sources of damage and loss data, there are data gaps concerning spatial and temporal coverage, estimated losses, and incomplete loss indicators. These challenges are coupled with restructuring Nepal’s administrative divisions in 2015, making spatial comparisons pre- and post-restructuring more difficult (BIPAD, 2020a).

Kathmandu Valley, Nepal, experiences a variety of single natural hazard and multi-hazard events against the backdrop of significant urbanisation, rapid population growth and climate change-related challenges (Nehren et al., 2013; Pradhan-Salike and Pokharel, 2017). In 2023, Kathmandu had about 1.57 million people in an area of about 49.4 km^2 (31,800 people per km^2) (The World Factbook, 2024). **Figure 1** presents six squatter settlements, with a total population of 7270 people in 2019 (Khanal and Khanal, 2019), out of 53 squatter settlements that are documented in Kathmandu Valley (DUDBC, 2010). Within Kathmandu Valley, many squatter settlements, 35 out of 53, are located along the banks of major river corridors like Bagmati (**Fig. 1**). This urban agglomeration experiences a breadth of single natural hazards (Pradhan et al., 2020; Whitworth

100 et al., 2020; Khatakho et al., 2021), with the potential for interrelationships to occur between these and across varying spatial and temporal scales.

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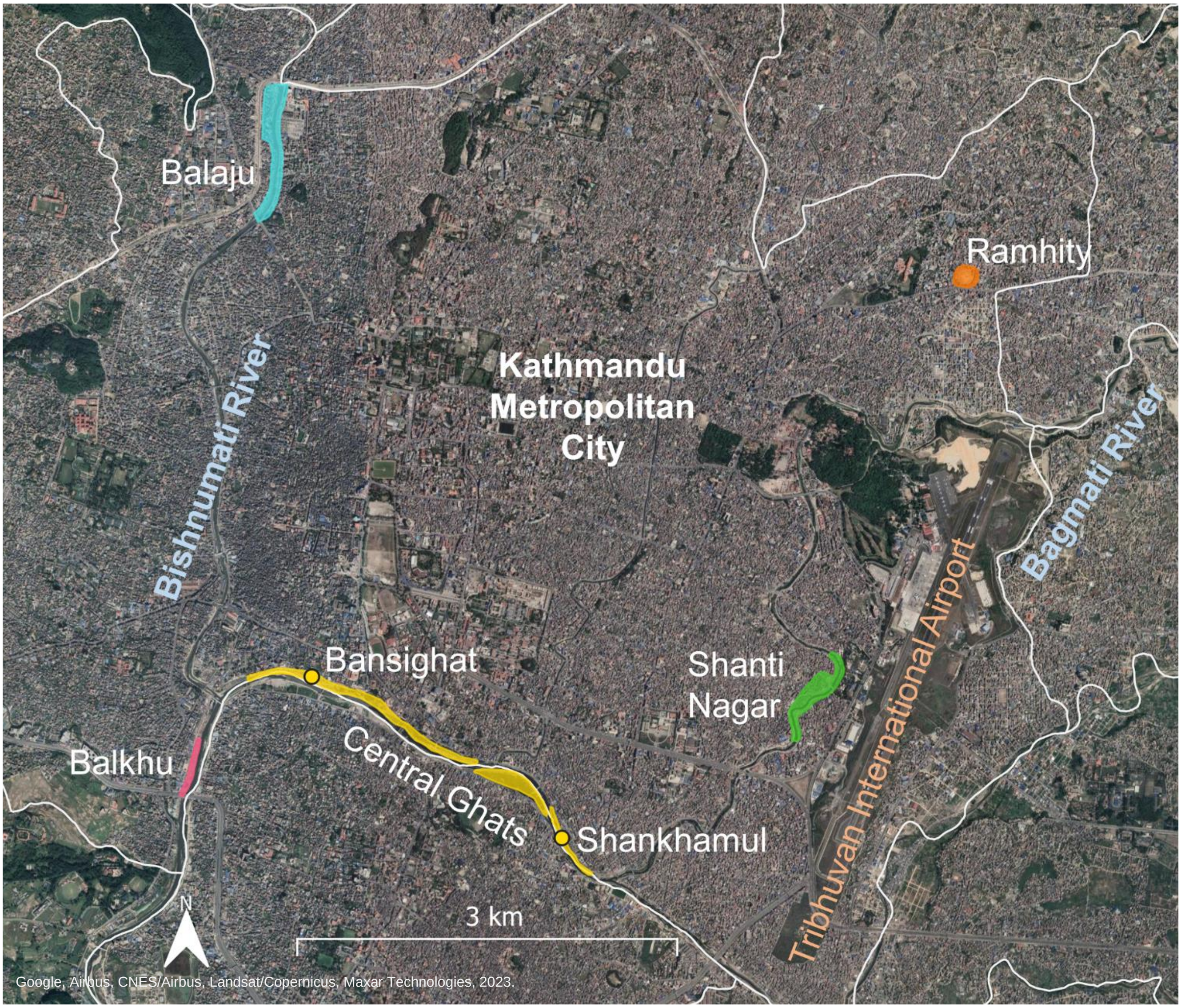

105 **Figure 1: Map showing the location of six selected squatter settlements in Kathmandu Valley, Nepal (Balaju—solid blue; Shanti Nagar—solid green; Ramhity—solid orange; Balkhu—solid pink; Central Ghats—solid yellow); main rivers (Bishnumati and Bagmati); Tribhuvan International Airport (orange text); and administrative boundaries (white solid line). [Location of squatter settlements adapted from: Dowse et al., 2014. Map data: © Google, Airbus, CNES/Airbus, Landsat/Copernicus, Maxar Technologies, 2023. Shapefile data: Survey Department, 2020.]**

Examples of the breadth of natural hazard events in Nepal and subsequent cascades of triggering other hazards or impacts include the following. 110

- The high-profile disaster of the Gorkha earthquake in April 2015 caused devastating impacts in Kathmandu Valley and beyond (Takai et al., 2016; Khatakho et al., 2021), with subsequent landslides on the periphery of the valley exacerbating these effects and prolonging the recovery effort (Kargel et al., 2015).
- Both fluvial and pluvial flooding are frequent in Kathmandu Valley during the mid-June to early September monsoon season. For example, during floods in early September 2021, heavy rainfall caused severe inundation across large areas of the valley and displaced hundreds of families in the Banshighat area (Chaulagain et al., 2023).
- Urban fires occur frequently and spread rapidly in areas of the valley with high population density (Khatakho et al., 2021), particularly in informal settlements where "marginalised" communities carry disproportionate hazard impacts and may have lower capacity to prepare and respond to hazard events (Brown et al., 2019; Dodman et al., 2022).

These earthquake, fire, flood and landslide events exemplify the complexity of the interactions between hazards and their impacts and highlight the need to understand how these events relate to the geographical contexts in which they occur.

The subsequent sections are organised as follows. **Section 2** details the methodology to systematically develop an overview of single hazards and multi-hazard interrelationships influencing Kathmandu Valley in two Excel databases (**Supplementary Material A. Kathmandu Valley Single Hazard Database** and **Supplementary Material B. Kathmandu Valley Multi-Hazard Interrelationship Database**). These sources provide evidence of hazards that have already influenced Kathmandu Valley and those that could potentially influence it, with descriptions of impacts where available in the sources. We then supplemented these blended source types with a workshop with stakeholders engaged in DRR in Kathmandu Valley. We used a similar methodology applied in Nairobi and Istanbul in the context of Tomorrow's Cities, which also looked at single hazards and multi-hazard interrelationships in both hub cities (Šakić Trogrlić et al., submitted). **Section 3** describes the results of both databases, followed by a discussion of findings in **Sect. 4**. We suggest this methodology can support understanding hazardscapes in other data-scarce urban contexts.

2 Methodology

This paper focuses on natural hazards and will not include technological, environmental, or biological hazards as defined by the UNDRR (2017). This section outlines our methodology for creating databases of single hazard and multi-interrelationships exemplars in a low-data availability context. These databases are based on blended sources, comprising different evidence types. Although the primary aim of the collation of sources was to evidence single hazards and multi-hazard interrelationships influencing Kathmandu Valley, we also reviewed all of the selected sources and noted impacts when they were described (Column 9 **in Supplementary Material A** and Column 6.1 in **Supplementary Material B**). In the context of this paper, we note that "influence" refers to a single hazard or multi-hazard interrelationship occurring in, or having a theoretical possibility of occurrence in Kathmandu Valley. Whereas "impact" refers to this occurrence or theoretical possibility of occurrence realising consequences that affect Kathmandu Valley. A workshop with practitioner stakeholders

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engaged in DRR in the context of Nepal supplements the databases, to add richness to the databases and incorporate additional multi-hazard interrelationship scenarios not included in the original exemplars.

Researchers are increasingly integrating blended (varied) sources of evidence to collate hazard events and their impacts. This use of blended sources of evidence builds upon Gill et al. (2020) regional interaction frameworks of multi-hazard interrelationships that use a "comprehensive, systematic, and evidenced" approach to collate multi-hazard interrelationships on a regional scale. Gustafsson et al. (2023) adopted this methodology to compile natural hazard interactions for Sweden, using reviews of the literature and government agency documents, a workshop conducted with experts in the field and statistical data. Our study builds upon Gill et al. (2020) methodology and develops it further to include multi-hazard interrelationship data on a much finer scale. In the case of Kathmandu Valley, this equates to ward level and individual urban poor settlements as the highest spatial resolution of data collated from the blended sources. The issue of data availability becomes more complex at finer spatial scales, which our study contributes towards resolving.

Section 2.1 outlines the commonalities between searches undertaken for single hazards and multi-hazard interrelationships. **Section 2.2** describes specific information relevant to the searches for single hazards and **Section 2.3** the multi-hazard interrelationships. **Section 2.4** closes with a description of a workshop undertaken with stakeholders engaged in DRR in Kathmandu Valley.

2.1 Systematic mapping of single hazards and multi-hazard interrelationships

This work builds upon previous studies utilising blended evidence sources to systematically review and collate multi-hazard events and impacts and supplement these sources with stakeholder knowledge (Neri et al., 2008; Gill et al., 2020; Taylor et al., 2020). Our methodology aims to be systematic but not comprehensive in gathering evidence for the potential for a specific hazard or multi-hazard relevant to Kathmandu Valley. Our methodology followed elements of a systematic mapping process, which aims to systematically find, evaluate, and integrate evidence using predefined guidelines (Grant and Booth, 2009; James et al., 2016). We outline the methodological steps as follows:

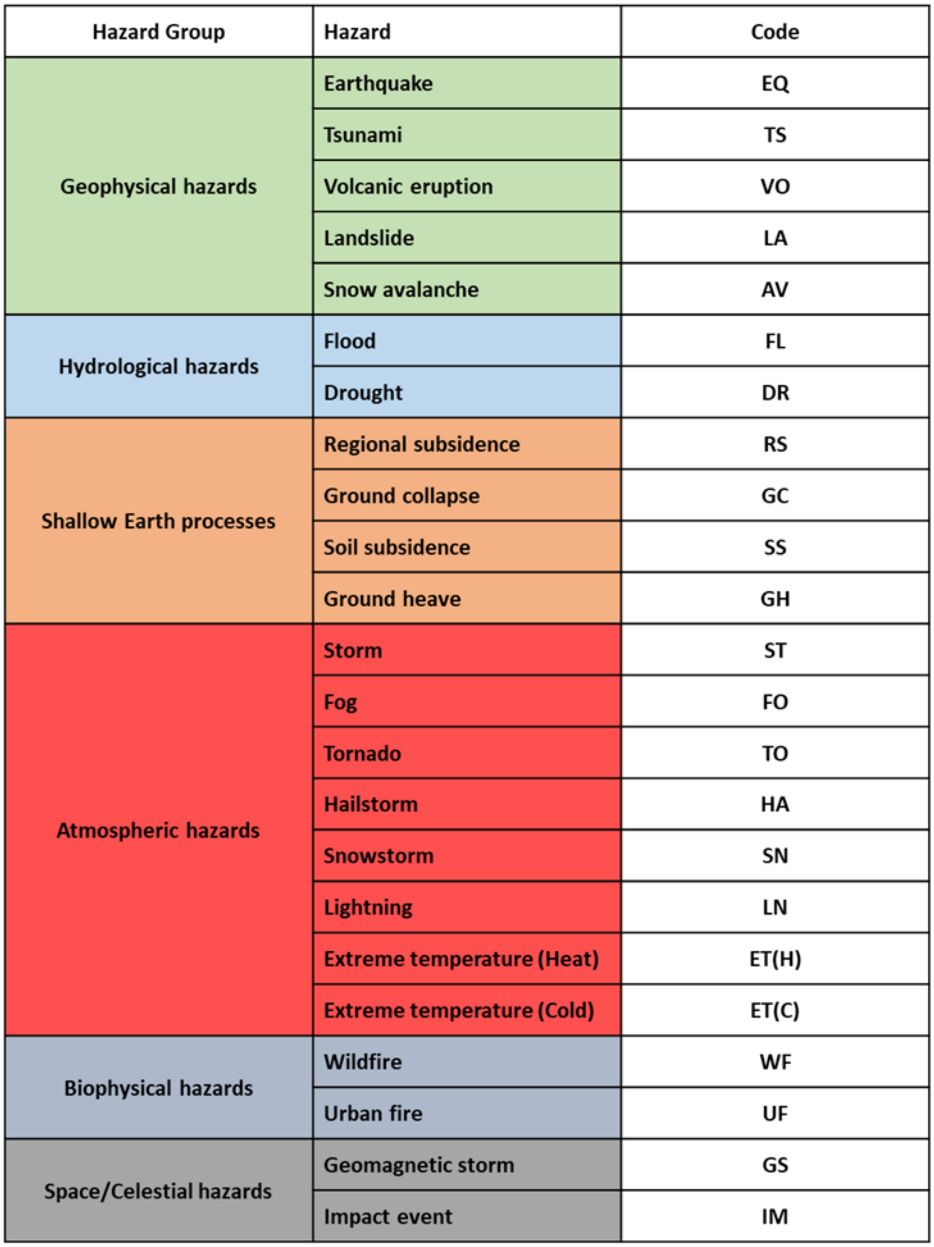
- We searched for exemplars of single hazards and multi-hazard interrelationships that either have influenced or could influence Kathmandu Valley in academic literature, grey literature, media, databases, and social media (e.g., YouTube videos).
    - We did not specify the spatial boundary around Kathmandu Valley; instead, we considered case studies to be relevant if they directly or indirectly influenced people, the economy, infrastructure, or the environment in the valley.
- Variations of the single hazard terms (e.g., singular and plural) and Kathmandu were used to find evidence for the single hazards.
- A simple Boolean search was used to find evidence for the multi-hazard interrelationships, with the following keywords: (a) the multi-hazard interrelationship type, (b) "Kathmandu Valley" AND impact*.

    - An example for earthquakes would be “earthquake* AND Kathmandu AND impact*”, where * represents zero or more characters (e.g., impacts, impacting).
    - We conducted searches in English as the authors do not speak Nepali, although ideally, we would complete the search in both languages.
- We applied our literature searches to two online databases of academic publications (Web of Science and Google Scholar). If these returned no results, we conducted similar searches in three online English-language Nepali newspapers (*The Himalayan Times*, *The Kathmandu Post* and *Nepali Times*), global and national disaster databases (e.g., EM-DAT; Nepal DRR Portal) and YouTube using their in-built search tools.
    - We reviewed the literature for each source type (academic literature, grey literature, media, databases, and social media (e.g., YouTube videos), and where available, we chose publications from 2010 onwards. We selected only one publication in the single hazard database (Supplementary Material A) and one publication in the multi-hazard interrelationship database (Supplementary Material B) that were published prior to 2010.
    - We focused on more recent events to capture the present hazardscape and its evolution. However, if recent events were not available, we searched for hazard event information extending further back in time.
    - If the Boolean search returned no results with this iteration, “impact*” was omitted from the search string. When searching for examples of multi-hazard interrelationship events, four Boolean search terms including “impact*” returned no results. In these cases, we removed “impact*” from each Boolean search term and conducted the searches again in the same search engines.
- We then selected exemplars of hazard events from these blended sources of academic literature, grey literature, media, databases, and social media.
    - When searches for a specific hazard or multi-hazard interrelationship returned more than ten results per search engine, we skimmed titles and abstracts for an indication of spatial and temporal occurrence, and we selected up to five pieces of evidence that documented previous influence in Kathmandu Valley (case studies) or had a theoretical possibility of influencing Kathmandu Valley.
    - If this examination of case study evidence returned no results for a particular hazard, we searched for any indication that the hazard may be theoretically possible of imparting impact in or around Kathmandu Valley.
    - Where we found no examples of specific single hazards or multi-hazard interrelationships impacting Kathmandu Valley, such as “tornado*” or “geomagnetic storm*”, we searched for evidence of the hazard occurring within, or having a theoretical possibility of occurrence, in Nepal with recorded or potential impacts in Kathmandu Valley.

2.2 Single hazards

We conducted systematic searches of academic literature, grey literature, media, databases, and social media to gather exemplars of single hazard events that have influenced or could potentially influence Kathmandu Valley. We started with the categorisation that Gill and Malamud (2014) developed with six hazard groups and 21 single natural hazards, recognising that there are other classifications (e.g., the hazard types described in the UNDRR-ISC Hazard Information Profiles (Murray, et al., 2021)). We added fog to the atmospheric hazard group and urban fire to the biophysical hazard group—where the nature of their fuel distinguishes urban fire and wildfire. Our hazard categorisation for Kathmandu Valley comprised six hazard groups divided into 23 single natural hazards (**Table 2**).

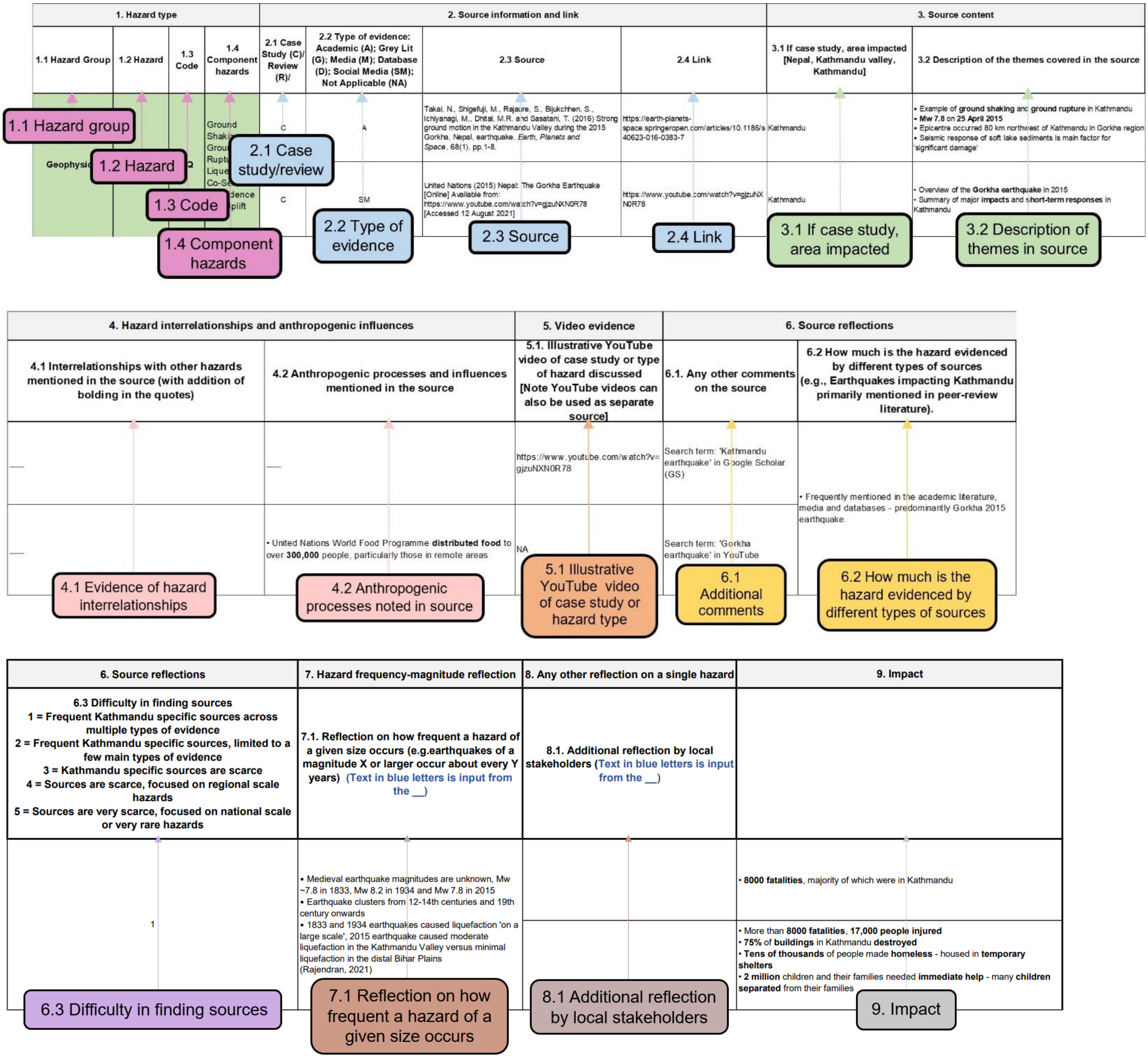
Table 2: Classification of the six hazard groups and 23 single natural hazards used in Kathmandu Valley. Adapted from the original classification developed by Gill and Malamud (2014).



Hazard Group	Hazard	Code
Geophysical hazards	Earthquake	EQ
	Tsunami	TS
	Volcanic eruption	VO
	Landslide	LA
	Snow avalanche	AV
Hydrological hazards	Flood	FL
	Drought	DR
Shallow Earth processes	Regional subsidence	RS
	Ground collapse	GC
	Soil subsidence	SS
	Ground heave	GH
Atmospheric hazards	Storm	ST
	Fog	FO
	Tornado	TO
	Hailstorm	HA
	Snowstorm	SN
	Lightning	LN
	Extreme temperature (Heat)	ET(H)
	Extreme temperature (Cold)	ET(C)
Biophysical hazards	Wildfire	WF
	Urban fire	UF
Space/Celestial hazards	Geomagnetic storm	GS
	Impact event	IM

The six hazard groups used here (**Table 2**) were geophysical, hydrological, shallow Earth processes, atmospheric, biophysical, and space/celestial hazards. We used the methodology described in the literature review in **Sect. 2.1** to conduct Boolean searches for single hazards and multi-hazard interrelationships that might occur in Kathmandu Valley. The examples of single hazards were collated into an Excel spreadsheet database **Supplementary Material A. Kathmandu Valley Single Hazard Database**, to summarise the collected evidence. A subset of this database is shown in **Fig. 2**. Each

Excel row in **Fig. 2** details evidence of a single hazard influencing Kathmandu Valley. Column thematic groups in the database include hazard type, source information and link, source content, hazard interrelationships and anthropogenic influences, video evidence, source and hazard frequency-magnitude reflections, and impact.



1. Hazard type				2. Source information and link				3. Source content	
1.1 Hazard Group	1.2 Hazard	1.3 Code	1.4 Component hazards	2.1 Case Study (C)/ Review (R)/	2.2 Type of evidence: Academic (A); Grey Lit (G); Media (M); Database (D); Social Media (SM); Not Applicable (NA)	2.3 Source	2.4 Link	3.1 If case study, area impacted [Nepal, Kathmandu valley, Kathmandu]	3.2 Description of the themes covered in the source
Geophysic		Q	Ground Shaki Grou Ruptu Lique Co-Se dence plift	C	A	Takai, N., Shigefuji, M., Rajaure, S., Bijukchhen, S., Ichiyanagi, M., Dhital, M.R. and Sasatani, T. (2016) Strong ground motion in the Kathmandu Valley during the 2015 Gorkha, Nepal, earthquake. *Earth, Planets and Space*, 68(1), pp.1-8.	https://earth-planets-space.springeropen.com/articles/10.1186/s40623-016-0383-7	Kathmandu	• Example of **ground shaking** and **ground rupture** in Kathmandu • **Mw 7.8** on **25 April 2015** • Epicentre occurred 80 km northwest of Kathmandu in Gorkha region • Seismic response of soft lake sediments is main factor for 'significant damage'
				C	SM	United Nations (2015) Nepal: The Gorkha Earthquake [Online] Available from: https://www.youtube.com/watch?v=gjzuNXN0R78 [Accessed 12 August 2021]	https://www.youtube.com/watch?v=gjzuNXN0R78	Kathmandu	• Overview of the **Gorkha earthquake** in 2015 • Summary of major **impacts** and **short-term responses** in Kathmandu

4. Hazard interrelationships and anthropogenic influences		5. Video evidence	6. Source reflections	
4.1 Interrelationships with other hazards mentioned in the source (with addition of bolding in the quotes)	4.2 Anthropogenic processes and influences mentioned in the source	5.1. Illustrative YouTube video of case study or type of hazard discussed [Note YouTube videos can also be used as separate source]	6.1. Any other comments on the source	6.2 How much is the hazard evidenced by different types of sources (e.g., Earthquakes impacting Kathmandu primarily mentioned in peer-review literature).
—	—	https://www.youtube.com/watch?v=gjzuNXN0R78	Search term: 'Kathmandu earthquake' in Google Scholar (GS)	• Frequently mentioned in the academic literature, media and databases - predominantly Gorkha 2015 earthquake.
—	• United Nations World Food Programme **distributed food** to over **300,000** people, particularly those in remote areas	NA	Search term: 'Gorkha earthquake' in YouTube	

6. Source reflections	7. Hazard frequency-magnitude reflection	8. Any other reflection on a single hazard	9. Impact
6.3 Difficulty in finding sources 1 = Frequent Kathmandu specific sources across multiple types of evidence 2 = Frequent Kathmandu specific sources, limited to a few main types of evidence 3 = Kathmandu specific sources are scarce 4 = Sources are scarce, focused on regional scale hazards 5 = Sources are very scarce, focused on national scale or very rare hazards	7.1. Reflection on how frequent a hazard of a given size occurs (e.g.earthquakes of a magnitude X or larger occur about every Y years) (Text in blue letters is input from the __)	8.1. Additional reflection by local stakeholders (Text in blue letters is input from the __)	
1	• Medieval earthquake magnitudes are unknown, Mw ~7.8 in 1833, Mw 8.2 in 1934 and Mw 7.8 in 2015 • Earthquake clusters from 12-14th centuries and 19th century onwards • 1833 and 1934 earthquakes caused liquefaction 'on a large scale', 2015 earthquake caused moderate liquefaction in the Kathmandu Valley versus minimal liquefaction in the distal Bihar Plains (Rajendran, 2021)		• **8000 fatalities**, majority of which were in Kathmandu
			• More than **8000 fatalities**, **17,000 people injured** • **75%** of **buildings** in Kathmandu **destroyed** • **Tens of thousands** of people made **homeless** - housed in **temporary shelters** • **2 million** children and their families needed **immediate help** - many **children separated** from their families

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230 **Figure 2: Extract of the Kathmandu Valley single hazards Excel spreadsheet (Supplementary Material A, Tab 1) for a section of the geophysical hazard group, including information on (1.1) hazard group, (1.2) hazard, (1.3) shorthand code of the hazard, (1.4) component hazards, (2.1) case study/review, (2.2) type of evidence, (2.3) source, (2.4) link to the source, (3.1) if the case study area was influenced (3.2) description of the themes covered in the source, (4.1) interrelationships with other hazards mentioned in the source, (4.2) anthropogenic processes, (5.1) YouTube evidence, (6.1) additional comments on the source, (6.2) how much different types of sources evidence the hazard, (6.3) difficulty in finding sources, (7) hazard frequency-magnitude reflection, (8) any other reflection on a single hazard, and (9) impact.**

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2.3 Multi-hazard interrelationships

Applying a similar systematic search to that described in **Section 2.2 Single hazards** above, we collated exemplars of multi-hazard interrelationships that have either influenced or could potentially influence Kathmandu Valley. Following the visualisation matrix developed by Gill and Malamud (2014), the 23 single hazards included in the methodology could interact to produce a maximum number of 23 × 23 = 529 theoretically possible interactions. Some of the single hazards or their interactions do not apply to Kathmandu Valley (e.g., tsunami and avalanche) or have a low probability of occurrence (e.g., impact event triggering earthquake; volcanic eruption triggering or increasing the probability of earthquake). We documented which low-probability events have a theoretical chance of occurring in, or could influence Kathmandu Valley. These interrelationships may be omitted from government or community preparedness plans yet pose significant impacts if they occur, especially if strategies are not in place to mitigate the effects.

Cognisant of these single hazard types, we searched the literature to determine how many theoretically possible hazard interactions have evidence of occurrence in Kathmandu Valley. We focused on two types of multi-hazard interrelationships (Gill and Malamud, 2017, p. 261):

- *Triggering relationship*: "One primary natural hazard triggers a secondary natural hazard."
- *Increased probability relationship*: "One primary natural hazard increases the likelihood of a secondary natural hazard."

We chose to search for triggering and increased probability multi-hazard interrelationships (consecutive hazards) to build on the same methodology used by Gill et al. (2020) and to increase the number of returned search results compared to less well-documented hazard interrelationship types, such as compound or coincident hazards (Gill et al., 2020). We collated the results into an Excel spreadsheet database **Supplementary Material B. Kathmandu Valley Multi-Hazard Interrelationship Database**, with primary and secondary hazard rows with an example of the database given in **Fig. 3**. This database includes detailed source information to gauge the reliability of the sources used to populate the database. Columns in the database are listed in the figure caption.

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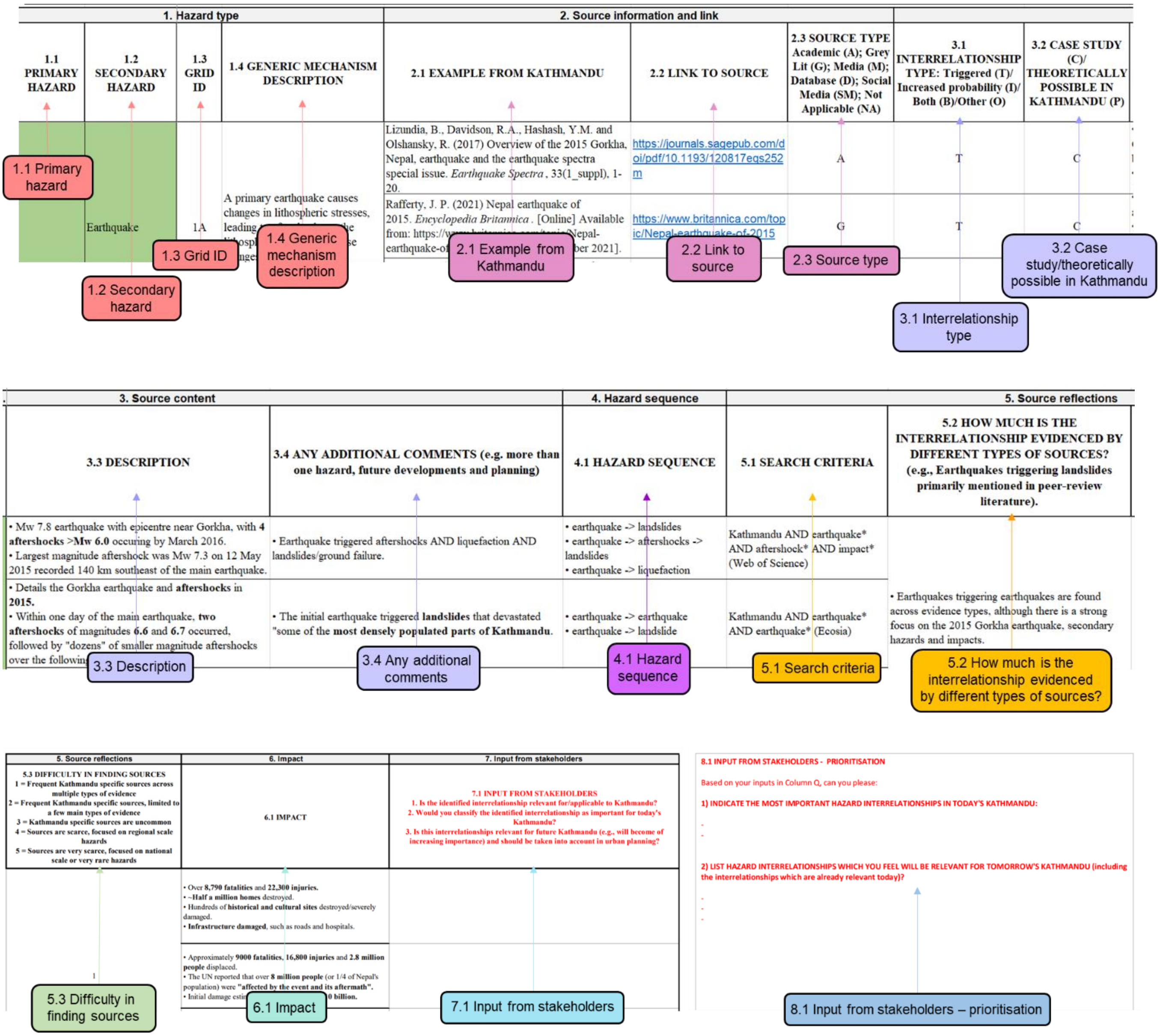


1. Hazard type				2. Source information and link				
1.1 PRIMARY HAZARD	1.2 SECONDARY HAZARD	1.3 GRID ID	1.4 GENERIC MECHANISM DESCRIPTION	2.1 EXAMPLE FROM KATHMANDU	2.2 LINK TO SOURCE	2.3 SOURCE TYPE Academic (A); Grey Lit (G); Media (M); Database (D); Social Media (SM); Not Applicable (NA)	3.1 INTERRELATIONSHIP TYPE: Triggered (T)/ Increased probability (I)/ Both (B)/Other (O)	3.2 CASE STUDY (C)/ THEORETICALLY POSSIBLE IN KATHMANDU (P)
	Earthquake	1A	A primary earthquake causes changes in lithospheric stresses, leading	Lizundia, B., Davidson, R.A., Hashash, Y.M. and Olshansky, R. (2017) Overview of the 2015 Gorkha, Nepal, earthquake and the earthquake spectra special issue. *Earthquake Spectra*, 33(1_suppl), 1-20.	https://journals.sagepub.com/doi/pdf/10.1193/120817eqs252m	A	T	C
				Rafferty, J. P. (2021) Nepal earthquake of 2015. *Encyclopedia Britannica*. [Online] Available from: https://w Nepal-earthquake-of ber 2021].	https://www.britannica.com/topic/Nepal-earthquake-of-2015	G	T	C

3. Source content		4. Hazard sequence	5. Source reflections	
3.3 DESCRIPTION	3.4 ANY ADDITIONAL COMMENTS (e.g. more than one hazard, future developments and planning)	4.1 HAZARD SEQUENCE	5.1 SEARCH CRITERIA	5.2 HOW MUCH IS THE INTERRELATIONSHIP EVIDENCED BY DIFFERENT TYPES OF SOURCES? (e.g., Earthquakes triggering landslides primarily mentioned in peer-review literature).
• Mw 7.8 earthquake with epicentre near Gorkha, with **4 aftershocks >Mw 6.0** occuring by March 2016. • Largest magnitude aftershock was Mw 7.3 on 12 May 2015 recorded 140 km southeast of the main earthquake.	• Earthquake triggered aftershocks AND liquefaction AND landslides/ground failure.	• earthquake -> landslides • earthquake -> aftershocks -> landslides • earthquake -> liquefaction	Kathmandu AND earthquake* AND aftershock* AND impact* (Web of Science)	• Earthquakes triggering earthquakes are found across evidence types, although there is a strong focus on the 2015 Gorkha earthquake, secondary hazards and impacts.
• Details the Gorkha earthquake and **aftershocks** in **2015.** • Within one day of the main earthquake, **two aftershocks** of magnitudes **6.6** and **6.7** occurred, followed by "dozens" of smaller magnitude aftershocks over the followin	• The initial earthquake triggered **landslides** that devastated "some of the **most densely populated parts of Kathmandu**.	• earthquake -> earthquake • earthquake -> landslide	Kathmandu AND earthquake* AND earthquake* (Ecosia)	

5. Source reflections	6. Impact	7. Input from stakeholders
5.3 DIFFICULTY IN FINDING SOURCES **1 = Frequent Kathmandu specific sources across multiple types of evidence** **2 = Frequent Kathmandu specific sources, limited to a few main types of evidence** **3 = Kathmandu specific sources are uncommon** **4 = Sources are scarce, focused on regional scale hazards** **5 = Sources are very scarce, focused on national scale or very rare hazards**	**6.1 IMPACT**	**7.1 INPUT FROM STAKEHOLDERS** **1. Is the identified interrelationship relevant for/applicable to Kathmandu?** **2. Would you classify the identified interrelationship as important for today's Kathmandu?** **3. Is this interrelationships relevant for future Kathmandu (e.g., will become of increasing importance) and should be taken into account in urban planning?**
	• Over **8,790 fatalities** and **22,300 injuries.** • **~Half a million homes** destroyed. • Hundreds of **historical and cultural sites** destroyed/severely damaged. • **Infrastructure damaged**, such as roads and hospitals.	
1	• Approximately **9000 fatalities**, **16,800 injuries** and **2.8 million people** displaced. • The UN reported that over **8 million people** (or 1/4 of Nepal's population) were **"affected by the event and its aftermath"**. • Initial damage esti **0 billion.**	

8.1 INPUT FROM STAKEHOLDERS - PRIORITISATION

Based on your inputs in Column Q, can you please:

1) INDICATE THE MOST IMPORTANT HAZARD INTERRELATIONSHIPS IN TODAY'S KATHMANDU:

-
-

2) LIST HAZARD INTERRELATIONSHIPS WHICH YOU FEEL WILL BE RELEVANT FOR TOMORROW'S KATHMANDU (including the interrelationships which are already relevant today)?

-
-
-

Figure 3: Extract of the Kathmandu Valley hazard interrelationships Excel spreadsheet (Supplementary Material B, Tab 3) for the earthquake (primary hazard) triggering earthquake (secondary hazard) section. This extract includes information on (1.1) primary hazard, (1.2) secondary hazard, (1.3) grid ID, (1.4) generic mechanism description, (2.1) example from Kathmandu Valley, (2.2) link to source, (2.3) source type, (3.1) interrelationship type, and (3.2) case study/theoretically possible in Kathmandu Valley, (3.3) description, (3.4) any additional comments, (4.1) hazard sequence, (5.1) search criteria, and (5.2) how much different source types evidence the hazard interrelationship, (5.3) difficulty in finding sources, (6.1) impact, (7.1) input from stakeholders, and (8.1) input from stakeholders – prioritisation.

2.4. Workshop on multi-hazard interrelationships and impacts

We facilitated a workshop to supplement the single hazards and multi-hazard interrelationships collated using the blended source types and examine their impacts. This 2-hour workshop, "Multi-hazard Interrelationships and Impacts in Kathmandu Valley" took place on 12 April 2023 with seven participants engaged in DRR in Kathmandu Valley. The workshop was organised into a presentation on single hazards and multi-hazard interrelationships in the context of Kathmandu Valley (30 minutes) followed by a 40-minute activity to gather participant perspectives on the Kathmandu Valley hazardscape. The activity was subdivided into components as follows:

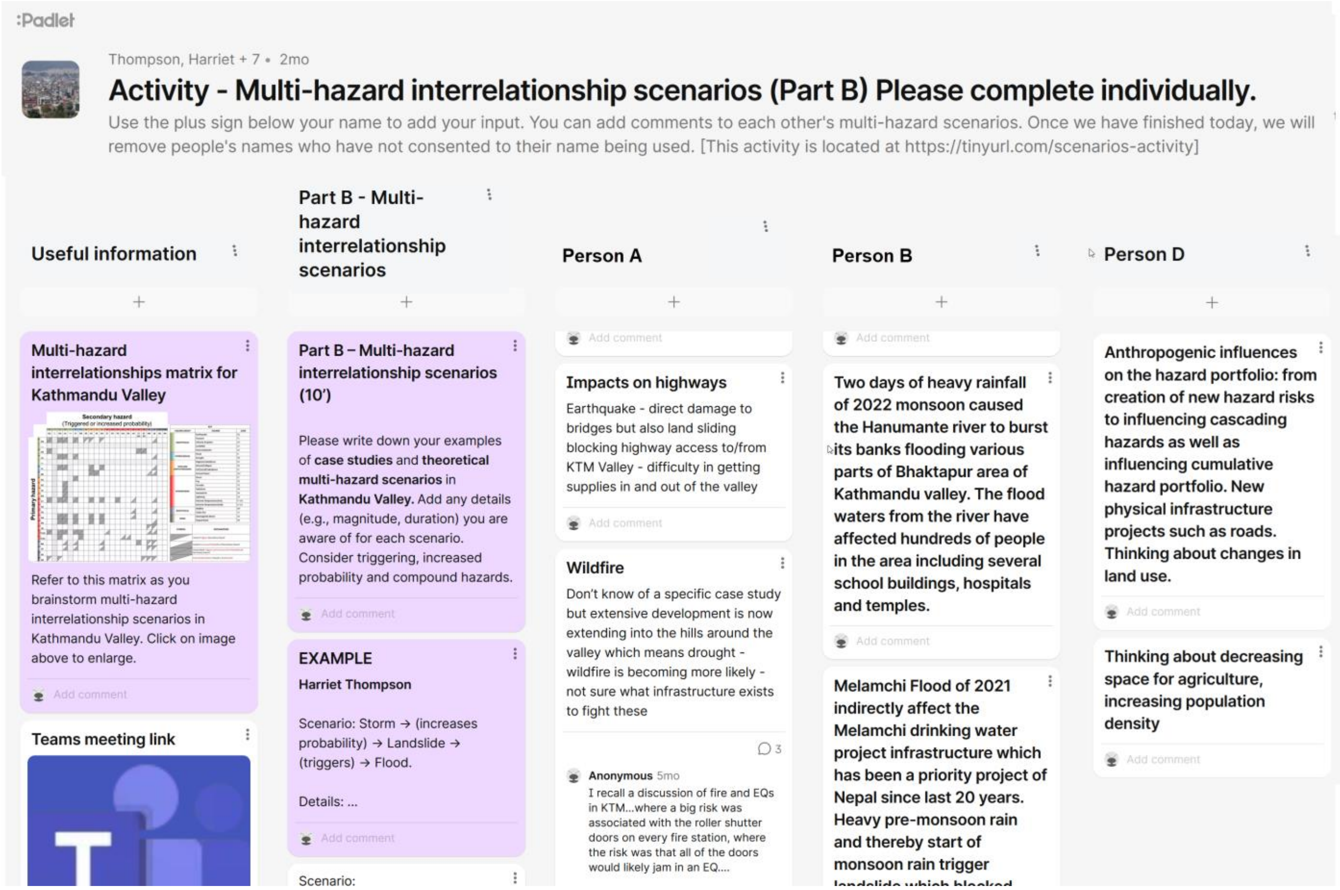
- Multi-Hazard Scenarios:
  - A. Group discussion (10');
  - B. Individual input in Padlet (10') and
  - C. Group discussion (10').
- Multi-hazard Impacts:
  - D. Individual input in Padlet (10').

After the activity there was a 10-minute discussion on the case study and theoretical multi-hazard scenarios that participants shared in the Padlet. Participants were encouraged to elaborate on details of the examples they shared, such as magnitude and duration of the events, and to consider the nature of the interrelationships (i.e., triggering, increased probability, and compound hazards). The motivation of this discussion was to examine the multi-hazard interrelationships and impacts that participants considered to be significant in the Kathmandu Valley context, and to relate these to the broader hazardscape.

The workshop aimed to co-produce multi-hazard interrelationship scenarios and their impacts through two workshop activities. We conducted the workshop on Teams as the participants attended virtually from the UK and Nepal. To minimise one potential effect of power asymmetries (Secor, 2010; Wolf, 2018), we aimed to balance the number of Nepali or Nepal-based (four) and British or UK-based (three) participants and female (two) and male (five) participants to support participants in feeling comfortable to share their knowledge and perspectives. These participants were selected based on their in-depth knowledge of the Kathmandu Valley context and existing connections built on pre-established working relationships (Wilmsen, 2008). We utilised the snowball sampling technique (Secor, 2010) to encourage participants to suggest any further colleagues who they thought might be interested in participating in the same workshop for us to contact. All participants gave informed consent for their participation, indicating their requested level of anonymity (i.e., any combination or none of the following: full name, position, institution). We facilitated the workshop under the King's College London Research Ethics Registration Number: MRSP-21/22-26736 as a Minimal Risk study.

During the workshop, we prompted discussion and knowledge sharing on multi-hazard interrelationships and multi-hazard impacts that could affect Kathmandu Valley in the future. We investigated these themes through group discussion in the main Teams meeting room, supported by the chat function, and individual input into Padlet (**Fig. 4**). The virtual pinboard within Padlet (**Fig. 4**) is an online resource that supports sharing ideas by posting content on a shared webpage. In the Padlet, we prompted participants to share their perspectives on the following themes:

1. *Multi-hazard Interrelationship Scenarios*
    - 305 Examples of case studies and theoretical multi-hazard scenarios (triggering, increased probability, and compound hazards) in Kathmandu Valley.
    - Additional information about multi-hazard scenarios (e.g., magnitude, duration).
2. *Multi-hazard Impacts*
    - Examples of multi-hazard impacts in Kathmandu Valley and their significance.
    - 310 Which social groups are most vulnerable to these impacts?



Thompson, Harriet + 7 • 2mo

Activity - Multi-hazard interrelationship scenarios (Part B) Please complete individually.

Use the plus sign below your name to add your input. You can add comments to each other's multi-hazard scenarios. Once we have finished today, we will remove people's names who have not consented to their name being used. [This activity is located at https://tinyurl.com/scenarios-activity]

Useful information

Multi-hazard interrelationships matrix for Kathmandu Valley

Refer to this matrix as you brainstorm multi-hazard interrelationship scenarios in Kathmandu Valley. Click on image above to enlarge.

Teams meeting link

Part B - Multi-hazard interrelationship scenarios

Part B – Multi-hazard interrelationship scenarios (10')

Please write down your examples of **case studies** and **theoretical multi-hazard scenarios** in **Kathmandu Valley.** Add any details (e.g., magnitude, duration) you are aware of for each scenario. Consider triggering, increased probability and compound hazards.

EXAMPLE

Harriet Thompson

Scenario: Storm → (increases probability) → Landslide → (triggers) → Flood.

Details: ...

Scenario:

Person A

Impacts on highways

Earthquake - direct damage to bridges but also land sliding blocking highway access to/from KTM Valley - difficulty in getting supplies in and out of the valley

Wildfire

Don't know of a specific case study but extensive development is now extending into the hills around the valley which means drought - wildfire is becoming more likely - not sure what infrastructure exists to fight these

3

Anonymous 5mo

I recall a discussion of fire and EQs in KTM...where a big risk was associated with the roller shutter doors on every fire station, where the risk was that all of the doors would likely jam in an EQ....

Person B

Two days of heavy rainfall of 2022 monsoon caused the Hanumante river to burst its banks flooding various parts of Bhaktapur area of Kathmandu valley. The flood waters from the river have affected hundreds of people in the area including several school buildings, hospitals and temples.

Melamchi Flood of 2021 indirectly affect the Melamchi drinking water project infrastructure which has been a priority project of Nepal since last 20 years. Heavy pre-monsoon rain and thereby start of monsoon rain trigger

Person D

Anthropogenic influences on the hazard portfolio: from creation of new hazard risks to influencing cascading hazards as well as influencing cumulative hazard portfolio. New physical infrastructure projects such as roads. Thinking about changes in land use.

Thinking about decreasing space for agriculture, increasing population density

Figure 4: Image of a portion of the populated virtual wall (Padlet) page used in the Multi-hazard Interrelationship Scenarios section of the 12 April 2023 workshop. The top of the image shows the title and brief description of the activity, with the participants' comments displayed below. We have replaced actual participant names with Person A, B, D. 315

Verbal group discussions were in a semi-structured format to support participants in sharing their perspectives on the themes with prompts to guide the conversation where needed. As facilitators, we aimed to balance the contribution of each participant to minimise domination of the discussions by one or more participants and to ensure that all participants felt comfortable sharing their thoughts. Many researchers have emphasised that when we work *with* individuals and communities, we must be aware of the contradictions of conducting fieldwork that centres equity and social justice in contexts where structural power imbalances exist between the researcher and those individuals and communities being researched (Subedi, 2006; Ozkazanc-Pan, 2012; Manning, 2018; Wolf, 2018). Throughout this study, we were reflexive about our positionalities, how our "Otherness" contributes towards power relations (Subedi, 2006; Mishra, 2018), and how we could minimise these effects in our research. Further discussion of positionality is presented in **Sect. 4.4** and explores the impact of on the workshop results of who was present or not present in the room.

3 Results

Here we give results of single hazard (**Sect. 3.1**) and multi-hazard interrelationship exemplars (**Sect. 3.2)** that have or could influence Kathmandu Valley as documented in blended source types. This is followed by insights from workshop participants (**Sect. 3.3),** including multi-hazard scenarios and their impacts.

3.1 Single hazards influencing Kathmandu Valley

Using the methodology described in **Sects. 2.1** and **2.2**, we compiled 58 sources of evidence for single hazards (**Supplementary Material A. Kathmandu Valley Single Hazard Database)** that have or might influence Kathmandu Valley. These sources evidenced 19 of the 21 single hazards given in **Table 2**, not including the following:

- *Tsunamis:* There are no large lakes or bodies of water near enough or in Kathmandu Valley for tsunami occurrence.
- *Snow avalanches:* In the Government of Nepal Disaster Risk Reduction Portal (Nepal DRR Portal, 2024), there are no recorded snow avalanche events in Bhaktapur, Kathmandu and Lalitpur (the three districts comprising Kathmandu Valley) from either the DesInventar Sendai (DesInventar Sendai, 2024) or Ministry of Home Affairs (Nepal DRR Portal, 2024) sources.

For the other 19 single hazards evidenced that might influence Kathmandu Valley, academic literature comprised the largest proportion of source types across the single hazards. All the sources were published from 2010 to 2021; the only exception was an example of soil subsidence published in 2002, as evidence of this hazard was challenging to find. Additionally, there have been no recorded tornadoes in Kathmandu Valley to date. However, we included tornado in the database due to the occurrence of Windstorm Parvana in southeast Nepal in March 2019. A team of researchers from The Small Earth Nepal and the country's Department of Hydrology and Meteorology reported the windstorm as Nepal's first recorded tornado (Mallapaty, 2019; Gautam, 2020).

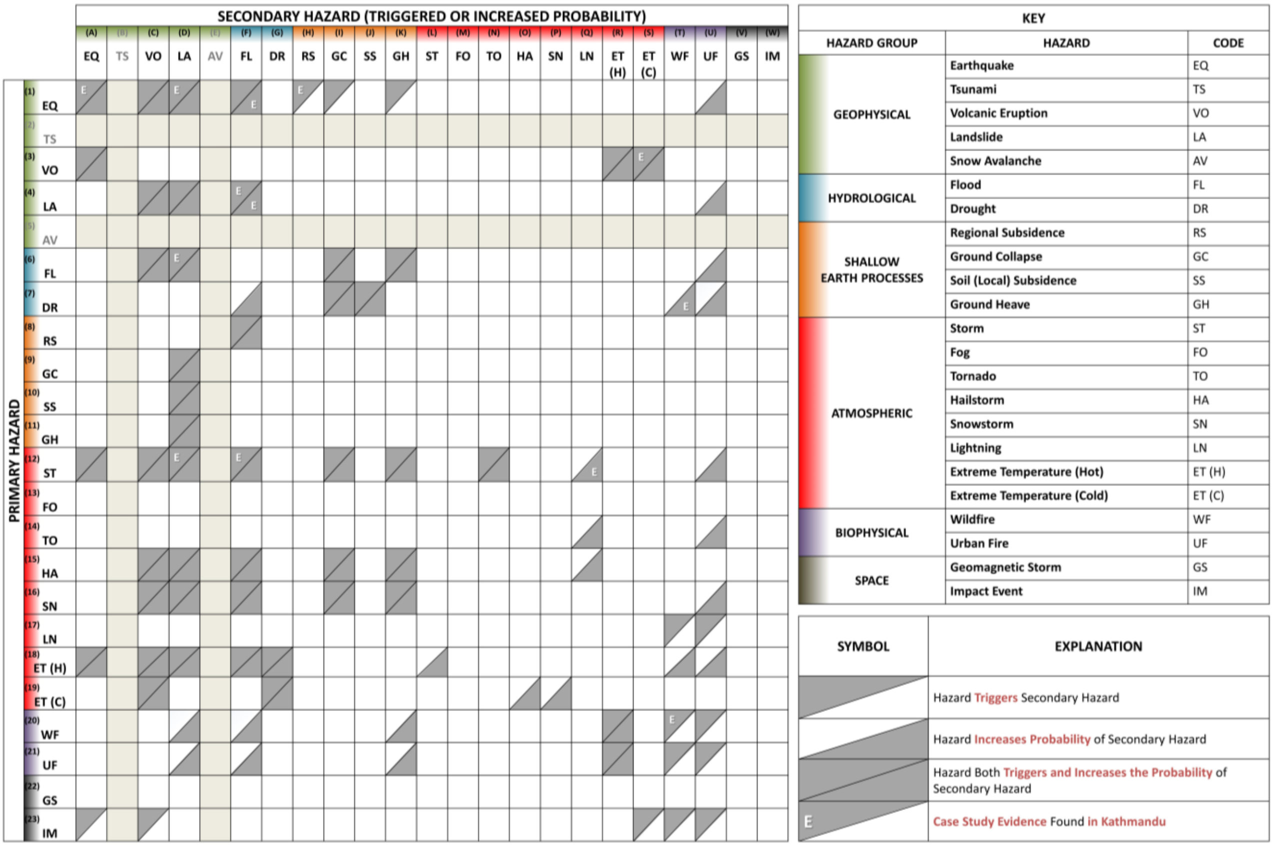
Across the single hazards, those which occur most regularly or with the most significant magnitudes, such as earthquake, flood, and urban fire, were most common across source types and often described impacts of the hazard in more detail. Conversely, it was more challenging to find evidence for hazards which occur less frequently (or have no direct evidence of occurrence, i.e., may only be theoretically possible in Kathmandu Valley) or have small magnitudes. These single hazards include volcanic eruption, soil subsidence and impact event. These limitations are explored further in **Sect. 4.5**.

3.2 Multi-hazard interrelationships influencing Kathmandu Valley

Searching for evidence of multi-hazard interrelationships that might influence Kathmandu Valley focused on triggering and increased probability relationships (**Sect. 2.3**) for primary to secondary hazards, using the 21 single hazard types in **Sect. 3.1** as our primary and secondary hazards. Using the methodology given in **Sect. 2.3**, we found 83 multi-hazard interrelationships (out of a potential of 21 x 21 = 441) of which 12 were directly evidenced using 21 blended sources (academic, grey literature, media, disaster databases; see **Supplementary Material B**).

- We use a 23-cell x 23-cell hazard interrelationship matrix (**Fig 5.; data in Supplementary Material B**) to visualise observed and theoretically possible interrelationships of primary to secondary hazards influencing Kathmandu Valley: *Triggering only:* 14 (17%) of 83.
- *Increased probability only:* 23 (28%) of 83.
- *Triggering and increased probability:* 46 (55%) of 83.

This interrelationship matrix, definitions of hazards (Gill and Malamud, 2014), hazard interrelationships (Gill and Malamud, 2014), and sources (Gill et al., 2020) are included in the **Supplementary Material B. Kathmandu Valley Multi-Hazard Interrelationship Database**.



KEY

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

SYMBOL	EXPLANATION
◤	Hazard Triggers Secondary Hazard
◢	Hazard Increases Probability of Secondary Hazard
■	Hazard Both Triggers and Increases the Probability of Secondary Hazard
E	Case Study Evidence Found in Kathmandu

Figure 5: 23-cell x 23-cell matrix of hazard interrelationships that are theoretically possible in Kathmandu Valley, Nepal. Primary hazards are on the y-axis, secondary hazards are on the x-axis, and the hazards are coded as detailed in the legend on the right. The hazards are categorised into geophysical (green), hydrological (blue), shallow earth processes (orange), atmospheric (red), biophysical (purple) and space (grey) hazard groups. The matrix shows where a primary hazard triggers a secondary hazard (upper left triangle shaded), a primary hazard increases the probability of a secondary hazard (lower right triangle shaded), a primary hazard both triggers and increases the probability of a secondary hazard (both triangles shaded), and where evidence is found for the interrelationship influencing Kathmandu Valley (E). This figure follows the visualisation and classification methodology developed by Gill and Malamud (2014) except that (i) tsunamic and snow avalanche hazards are not found in Kathmandu Valley and therefore not considered here for interrelationships (Rows 2, 5 & Columns B, E, greyed out), and (ii) fog and urban fire hazards are added as they are relevant in Kathmandu Valley (Rows 13, 21 and Columns M, N).

The multi-hazard interrelationship matrix in **Fig. 5** visualises which scenarios have influenced or could potentially influence Kathmandu Valley. We have justified interrelationships where a primary hazard increases the probability of urban fire (e.g., 1U: earthquake increases the probability of urban fire) but not wildfire by considering anthropogenic processes as an intermediary step. For example, an earthquake could rupture gas mains or cause electricity pylons to fall, increasing the probability of an urban fire. The figure provides an efficient tool for quickly assessing which multi-hazard interrelationship pairs or cascades are relevant for the Kathmandu Valley context. Within these interrelationship types, the reader can rapidly determine the proportion of triggering interrelationships, increased probability interrelationships and both of these interrelationships, in addition to where we found direct evidence for a multi-hazard interrelationship influencing the Kathmandu Valley context. **Figure 6** illustrates two multi-hazard scenarios that either have influenced or could potentially influence Kathmandu Valley using the multi-hazard interrelationship matrix in **Fig. 5**.

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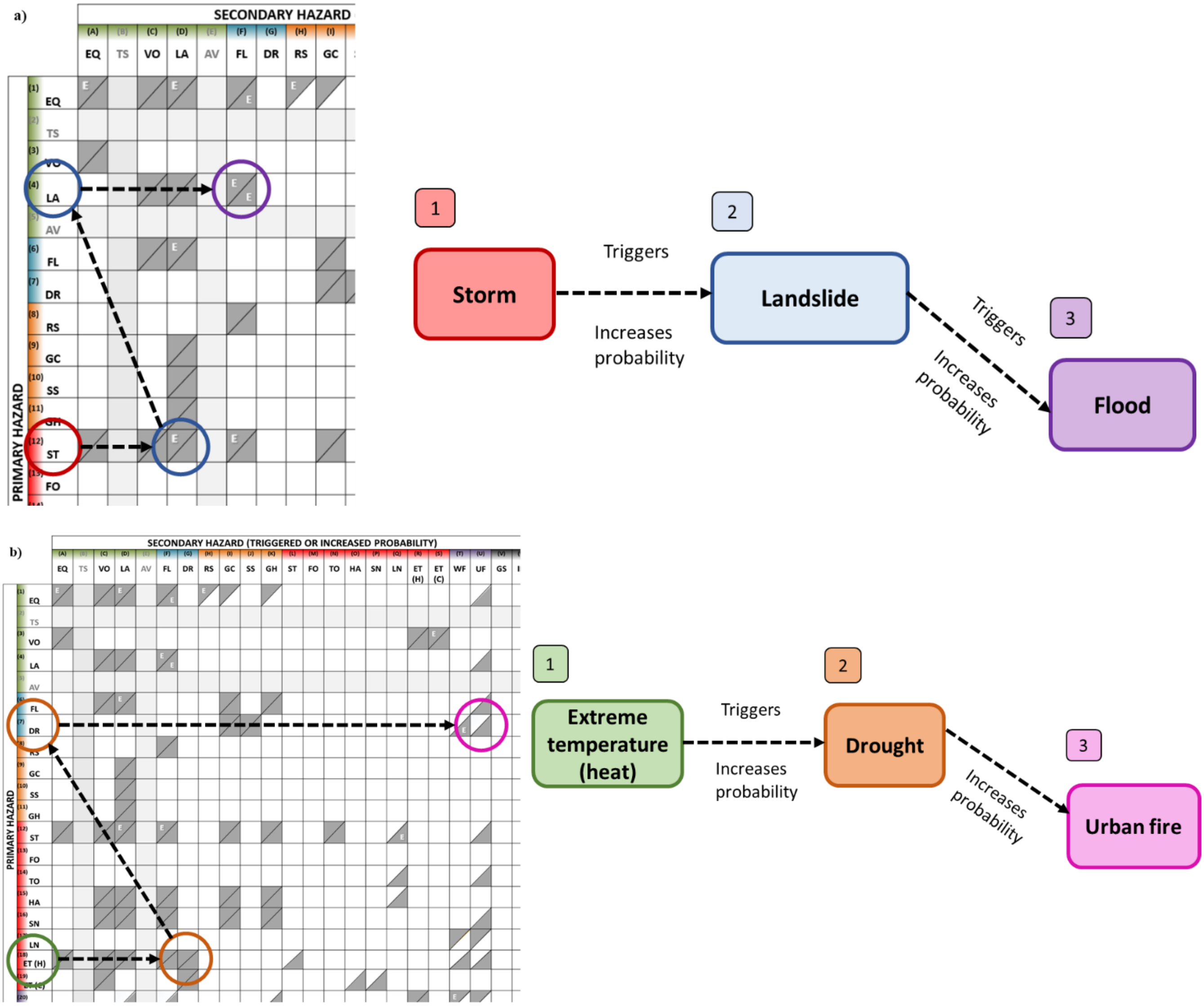

Figure 6: Two examples of multi-hazard scenarios that could influence Kathmandu Valley, Nepal: a) storm to landslide to flood, and b) extreme temperature (heat) to drought to urban fire. Both multi-hazard scenarios could involve triggering or increased probability interrelationships and are illustrated using the hazard interrelationship matrix (see Figure 5). Multi-hazard scenario b), extreme temperature (heat), to drought to urban fire, has evidence of influence in Kathmandu Valley. Primary hazards are shown on the y-axis, secondary hazards are shown on the x-axis, and the hazards are coded as detailed in the legend in Figure 5. The matrix shows where a primary hazard triggers a secondary hazard (upper left triangle shaded), a primary hazard increases the probability of a secondary hazard (lower right triangle shaded), a primary hazard both triggers and increases the probability of a secondary hazard (both triangles shaded), and where evidence is found for the interrelationship influencing Kathmandu Valley (E).

The two multi-hazard scenarios in **Fig. 6** clarify how to interpret which interrelationships are relevant to the Kathmandu Valley context as shown in **Figure 5**. For instance, the two multi-hazard scenarios show the interrelationships between single hazard types and hazard groups, where a) describes the cascade from a primary atmospheric hazard to a secondary

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geophysical hazard to a tertiary hydrological hazard, and b) from a primary atmospheric hazard to a secondary hydrological hazard to a tertiary biophysical hazard. These two examples emphasise the interconnections between various Earth systems and the complex nature of interactions between single hazards, in turn further supporting the need for holistic multi-hazard approaches to mitigating disaster risk. Additionally, we shared **Fig. 6** with workshop participants to illustrate the value of the multi-hazard interrelationship matrix in extracting relevant multi-hazard scenarios.

The accompanying database (**Supplementary Material B**) provides further information for each multi-hazard interrelationship included in **Fig. 5 and Fig. 6**, including hazard type, source information, source content, hazard sequence, source reflections, impact, and stakeholder input. This additional information provides greater context to the figures and enables the methodology to be scalable to other geographical regions, as discussed in **Sect. 4.6**.

Searching for evidence of multi-hazard interrelationships was more challenging than single hazards. The source types primarily discuss single hazards and their impact in some depth yet neglect to describe interrelationships between hazards and may only superficially state hazard impacts. We explore this challenge in greater depth in **Sect. 4.2**.

3.3 Insights from workshop participants

We planned and facilitated a 2-hour workshop with practitioner stakeholders engaged in DRR work in Kathmandu Valley following the methodology described in **Sect. 2.4**. To supplement the single hazards and multi-hazard interrelationships blended evidence sources in **Supplementary Material A and B,** we designed the co-production of multi-hazard interrelationship scenarios to gather stakeholder perspectives on current applications of multi-hazard knowledge, opportunities for stakeholders to use multi-hazard scenarios, and implementation of these scenarios in DRR strategies in Kathmandu Valley. The main outputs of the workshop (**Sect. 3.3.1 and 3.3.2**) were the production of multi-hazard interrelationship scenarios and multi-hazard impacts. Participants discussed these scenarios as a group before independently noting their own examples on the Padlet pages. Through the workshop, we identified which multi-hazard interrelationships and impacts are most common, which are stakeholder priorities, and which are overlooked but may have significant implications in the future as discussed in **Sect. 4.4**.

3.3.1 Multi-hazard interrelationship scenarios

The stakeholder workshop had an activity of 40 minutes where participants individually designed multi-hazard interrelationship scenarios and discussed these scenarios as a group. Participants individually added these scenarios to a Padlet page (virtual pinboard), also noting whether it was a case study that had previously influenced or a theoretical example that might influence Kathmandu Valley in the future. Participants were encouraged to add any additional contextual information, such as comments about vulnerability and exposure, where known. **Table 3** shows 11 multi-hazard interrelationship scenarios that the seven participants shared on the Padlet page.

Table 3: List of 11 multi-hazard interrelationship scenarios that include two or more hazards shared by participants in a virtual wall (Padlet) during a workshop. Each scenario is either a Case Study (CS) that has influenced Kathmandu Valley or a Theoretical Example (TE) that could influence Kathmandu Valley in the future. Any additional notes that provide context to the scenario are also given, including direct quotes by participants and summaries of information shared by participants.

Scenario Number	Multi-hazard Interrelationship Scenario	Case Study (CS) or Theoretical Example (TE)	Additional Notes Including Participant Quotes
1	**Earthquake** -> Damage to infrastructure + **Landslide** -> Blocked supply access to Kathmandu Valley	TE	
2	**Drought** -> **Wildfire**	TE	Exacerbated by development extending into hills surrounding the valley.
3	**Earthquake** -> **Urban Fire**	TE	Shutter doors in fire stations could jam in an earthquake; restricted fire engine access due to road debris.
4	**Storm** -> **Flooding** -> Infrastructure damage + Restricting Transportation	CS	"Two days of heavy rainfall [during the] 2022 monsoon caused the Hanumante river to burst its banks flooding various parts of Bhaktapur area of Kathmandu Valley. The floodwaters from the river affected hundreds of people in the area including several school buildings, hospitals and temples." – Kathmandu Workshop Participant B
5	**Storm** -> **Landslide** -> **Flood**	CS	"Melamchi Flood of 2021 indirectly affect[ed] the Melamchi drinking water project infrastructure which has been a priority project of Nepal [for the] last 20 years. Heavy pre-monsoon rain and thereby start of monsoon rain trigger[ed] landslide which blocked Melamchi river for about 45 minutes, and when that burst, [the] flood [caused] by that had significant impact on downstream communities." – Kathmandu Workshop Participant B
6	**Earthquake** -> (increasing probability of) -> **Fire**	TE	Considering the impact of seasonality on hazard cascades: here, an earthquake occurring in the dry season.
7	**Earthquake** -> (cascading) **Landslide** -> (cascading) -> Sedimentation -> **Flood**	TE	Considering the impact of seasonality on hazard cascades: here, an earthquake occurring in the monsoon season.
8	**Storm** -> **Flood**	CS	"Kalanki Settlement Area flooded in 2019. In 2019, 3-days heavy precipitation in Kathmandu resulted [in] flooding in [a] small stream near Kalanki city area. Water filled inside houses and roads blocked. Many 2-wheeler vehicles swept away. Lots of core city area in Kathmandu was flooded [at] that time." – Kathmandu Workshop Participant F
9	**Wildfire** -> **Air pollution**	CS	"Air pollution due to Forest Fire. In 2021, Nepal battled its worst forest fires in years. As per the officials, the fire smoke waft[ed] across [the] mountains and sour[ed] the air as it settle[d] into the bowl that holds the capital city of Kathmandu. People were asked to stay in and Tribhuvan University class[es were] also suspended for few days to avoid pollution. – Kathmandu Workshop Participant F
10	Haphazard development + Faulty electrics -> **Urban fire**	TE	
11	Haphazard construction and development + Soil conditions -> **Ground displacement**	TE	

Of the 11 multi-hazard interrelationship scenarios shared by participants (**Table 3**), the majority include hazards from the biophysical, geophysical, and hydrological hazard groups. Five scenarios include fire (biophysical), four include earthquake (geophysical), three include landslide (geophysical), and three include heavy rainfall or precipitation (hydrological). Although most (7 of 11) of the proposed scenarios are simple primary to secondary hazard interactions, there are some examples of more complex interactions. Scenarios 6 and 7 in **Table 3** illustrate how meteorological conditions can significantly influence the unfolding scenario and its impacts. If an earthquake occurs in the dry season, it is more likely to increase the probability of fire. Conversely, in the monsoon season, an earthquake could cascade into a landslide, increasing river sedimentation and the likelihood of flooding. These contrasts in environmental conditions illustrate how seasonality can significantly impact hazard cascades.

In the 20-minute group discussion, participants cited anthropogenic factors as influencing hazards. For example, Scenario 2 in **Table 3** (drought -> wildfire) states that development into the hills surrounding Kathmandu Valley exacerbates the hazard interrelationship and the resulting impacts. This challenge was echoed in Scenario 10 (haphazard development + faulty electrics -> urban fire) and Scenario 11 (haphazard construction and development + soil conditions -> ground displacement), which detail how rapid, and sometimes “unmanaged” urbanisation increases the exposure of communities to multi-hazard events in Kathmandu Valley.

The multi-hazard scenarios proposed by participants support those in the multi-hazard matrix (developed before the workshop) in **Fig. 5**. Scenarios 4 (rainfall -> flood) and 5 (rainfall -> landslide -> flood) in **Table 3** are not included in the original matrix as rainfall is grouped under storm hazard. The same is true of Scenario 8 (rainfall -> flood). The only three scenarios in **Table 3** that are not present in the original matrix in **Fig. 5** are those involving air pollution (Scenario 9: wildfire -> air pollution) and processes of rapid urbanisation (Scenario 10: haphazard development + faulty electrics -> urban fire, and Scenario 11: haphazard construction and development + soil conditions -> ground displacement). Building upon Gill and Malamud (2014) hazard interaction framework, we decided only to include natural hazards in the multi-hazard interrelationship matrix. Including anthropogenic hazards and related processes could form the basis of future developments of this work.

3.3.2. Multi-hazard impacts

In the final component of the 40-minute workshop activity, we asked participants to individually add two or three examples of impacts from multi-hazard interrelationship scenarios in Kathmandu Valley to a Padlet page (virtual pinboard). We requested that participants focused on impacts which they believed are most significant for people in Kathmandu Valley and, where possible, to list who (e.g., which social group) might be most affected by these impacts. **Table 4** shows 12 impact examples that the seven participants shared on the Padlet page.

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470 **Table 4: List of 12 impact examples shared by participants in a virtual wall (Padlet) during a stakeholder workshop. The table lists the number of the impact example, direct quotes shared by participants, and the hazard types causing the impacts.**

Impact Example Number	Direct quote shared by participant	Hazard types causing impacts
1	"Communities along highways into valley - high exposure to EQ [earthquake] + landslide damage, but also dependent on traffic for livelihoods."	Earthquake and landslide
2	"Indirect impacts: still only limited capacity to respond to disasters at municipality or provincial level, so direction + materials must still come from capital. So if KTM [Kathmandu] is responding to an event, other parts of the country will have to wait"	All theoretically possible hazards
3	"Flood has a direct impact on urban poor mainly those living in a temporary shelter built in the bank of Bagmati river. Every year, flood[s] terrify those who are living in the informal settlements. These temporary households [are] also affected by windstorm. Assets damaged and or assets los[t] due to these hydro-climatic impacts have direct connection with livelihoods of the people."	Flood and storm (windstorm)
4	"Multi-hazard scenarios increase 'uncertainty' which affect primarily migrants and marginalized dwellers."	All theoretically possible hazards
5	"Multi-hazards effect on land uses increasing inundation and landslides which affect farmers, women and labour."	All theoretically possible hazards
6	"Flooding of homes and businesses impacts society particularly those who are more vulnerable, migrants."	Flood
7	"Landslides impact physical infrastructure, livelihoods, landscapes and increases uncertainty in people."	Landslide
8	"Migrants who cannot vote in KV's [Kathmandu Valley] cities are particularly vulnerable to impacts."	All theoretically possible hazards
9	"Impacts of EQ [earthquake] or large monsoon on hydropower function and electricity supply to KTM [Kathmandu], via direct damage to infrastructure (shaking/landslides) or protracted sedimentation > impact upon wider power grid > impacts all users of power via load shedding."	Earthquake and storm (monsoon rain)
10	"Socio-economic impact, gender inequality, development challenge and challenge in meeting development goals. Increased vulnerability of ecosystem and communities."	All theoretically possible hazards
11	"Direct Impact: human death, building damage, physical infrastructures such as road, bridge etc."	All theoretically possible hazards
12	"[But needs to think about] jobs and livelihood, social-cultural and organizational impacts (e.g. system, ethics, indigenous, organizations, traditional festiv[iti]es), health infrastructure, education, and micro-infrastructures."	All theoretically possible hazards

The 12 impact examples shared by workshop participants focus on hazard types that have the most significant impacts on people in Kathmandu Valley, namely earthquake, flood, landslide and storm (monsoon rain and windstorm). Participants also described impacts that could more broadly apply to all hazard types that are theoretically possible in Kathmandu Valley. Although some impacts shared by participants were direct and tangible in nature, many examples considered indirect and intangible impacts with attention directed towards the complex interactions between impacts, and socio-political and anthropogenic factors. Indeed, the impact examples shared by workshop participants in **Table 4** can be divided into three main themes: cascading impacts, disaggregated impacts, and impacts on "marginalised" communities, which we discuss in **Sect. 4.3.2**. Within this discussion section (**Sect. 4.3.2**), we explore the positive feedback loop between multi-hazard events, increasing informality, and the interrelationships between "marginalisation" and vulnerability in the Kathmandu Valley context in greater detail.

4 Discussion

In this discussion, we highlight five major themes. First, we discuss frequency magnitude relationships, giving some examples for single hazard events (**Section 4.1**). Next, we consider the challenges in finding evidence of multi-hazard interrelationships in the blended source types (**Section 4.2**), detailing specific multi-hazard interrelationships and reasons for fewer multi-hazard interrelationship exemplars. Following this, we discuss findings from the workshop with stakeholders engaged in DRR strategies in Kathmandu Valley (**Section 4.3**) and the single hazard and multi-hazard interrelationship impacts described in the blended evidence types (**Section 4.4**). We consider the limitations within the methodology (**Section 4.5**). Finally, we outline the scalability of our methodology to other data-scarce urban settings (**Section 4.6**) and suggest future research directions (**Section 4.7**).

4.1 Frequency magnitude information

The availability of frequency-magnitude information varied significantly by single hazard type. Here we present some examples for the following single hazards:

Earthquake: For example, geological records show that significant earthquakes have influenced Kathmandu Valley several times in the last 800 years (Rajendran, 2021), namely in 1255, 1344, 1833 (Mw ~7.7), 1934 (Mw 8.2) and April 2015 (Mw 7.8). The pulse of earthquakes in the 12th and 14th centuries (that may have liquefied the valley region), succeeded by a period of inactivity until the 17th century, has led to a proposed cyclicity of seismicity in the Himalaya region (Rajendran, 2021).

Volcanic eruption: Another geophysical hazard that has well-documented frequency-magnitude relationships is volcanic eruption. A study by Liang et al. (2019) found that since 1650, large volcanic eruptions in tropical regions most probably caused severe pre-monsoon droughts in the central Himalayas. Tree ring records show that of eight large volcanic eruptions in Southeast Asia since 1650, six were associated with droughts in Langtang, Manasulu and Sagarmatha valleys in central Nepal (Liang et al., 2019).

Flooding: Considering hydrological hazards, a modelling study by Pradhan-Salike and Pokharel (2017) showed that urbanisation and future climate change will increase pluvial flooding in Kathmandu Valley. For a 25-year return period, they forecasted a 40% increase in flooding (Salike and Pokharel, 2017).

Tornado: Within the atmospheric hazards group, storm occurrence in Nepal is not frequent; Windstorm Parvana was the largest-scale storm in over seventy years (Gautam et al., 2020). Parvana was described as the first recorded tornado in Nepal, with a mean speed of 250 km per hour and an estimated size of 200 km by 200 km (Chhetri et al*.*, 2019).

Taking these exemplars of hazard events, rather than an exhaustive compilation, it is apparent that specific hazards within the geophysical, hydrological, and atmospheric hazard groups have the most quantitative frequency-magnitude information. The remaining hazard groups – shallow Earth processes, biophysical and space/celestial – have some frequency-magnitude information for some hazard types, but this is typically limited to qualitative descriptions.

4.2 Challenges in finding case study evidence of multi-hazard interrelationships that have influenced Kathmandu Valley

Based on the limited amount (we found 21 sources) of multi-hazard interrelationship case studies that have previously influenced Kathmandu Valley, we identify the following challenges:

- Globally, there is a focus on reporting and describing single hazards instead of detailed information on hazard interrelationships.
- Globally, research and understanding of single hazards are more established than for multi-hazard interrelationships.

For finding case studies of single and multi-hazard interrelationships that have influenced Kathmandu Valley, we found it much easier to find case studies for single hazards (15 out of 19 single hazards) compared to multi-hazard interrelationships (12 out of 83). This low proportion of direct evidence for multi-hazard interrelationships is likely due to a lack of documented multi-hazard events in Kathmandu Valley and the fact that we only searched for evidence in English language sources. Within these exemplars of multi-hazard interrelationships, we identified that there were differences in the number of sources available for the interrelationships of each primary hazard. For example, case studies of earthquake triggering landslide, earthquake triggering earthquake, storm triggering landslide, and storm triggering flood were the most prevalent multi-hazard interrelationships in the literature. Conversely, we found no case study evidence for earthquake triggering volcanic eruption or ground heave triggering landslide. These challenges contribute to hazard data scarcity in Kathmandu Valley, specifically regarding cascading events and their impacts. Within our research, we could partially resolve these issues by searching non-online sources (e.g., archival material) and engaging in discussions with stakeholders, as **Sect 4.5** outlines.

4.3 Workshop findings

4.3.1. Multi-hazard interrelationship scenarios

The findings from the workshop, conducted with stakeholders engaged in DRR in Kathmandu Valley, supplemented the exemplars collated from blended sources of evidence described above. The workshop provided a forum for participants to share their perspectives on multi-hazard interrelationship scenarios and multi-hazard impacts affecting Kathmandu Valley. The diversity in the subject backgrounds of participants provided a broad range of insights that complements the information collated from the blended evidence types (academic literature, grey literature, media, databases, and social media) described in **Sect. 3.1** and **Sect. 3.2** (Matanó et al., 2022). The discussions produced some novel findings concerning the hazardscape in Kathmandu Valley, specifically in producing multi-hazard interrelationship scenarios for the context of Kathmandu Valley by stakeholders working within DRR. These multi-hazard interrelationship scenarios complement existing literature that documents the variety of multi-hazard scenarios that have influenced Kathmandu Valley and those that could theoretically influence the valley in the future (Gautam et al., 2020; Gill et al., 2021a; Khatakho et al., 2021).

The discussion of multi-hazard interrelationship scenarios centred around biophysical, geophysical, and hydrological hazard groups and simple triggering or increased probability interrelationships. In both case studies and theoretical examples, participants described how anthropogenic factors increased the severity of multi-hazard impacts and altered response efforts following hazard events. A systematic multi-hazard risk assessment of Kathmandu Valley conducted by Khatakho et al. (2021) found that old settlements, densely populated settlements, and the central valley were the most risk-prone regions in the valley, supporting the participants' expert knowledge of the Kathmandu Valley context. Participant A commented on how the extension of development into the hills surrounding Kathmandu Valley has increased the exposure of communities to multi-hazard impacts, particularly when coupled with heightened social vulnerabilities such as lower socio-economic status or "marginalised" identities. Indeed, urban poor communities, and other "marginalised" groups, experience heightened risk due to high exposure to multi-hazards and social vulnerabilities (Pelling et al., 2004). The multi-hazard scenarios developed by participants provided further evidence for multi-hazard interrelationships listed in the multi-hazard interrelationship matrix for Kathmandu Valley in **Fig. 5**. Additional scenarios that supplement those included in the matrix are Scenarios 9 (wildfire -> air pollution), 10 ("haphazard development" + faulty electrics -> urban fire), and 11 ("haphazard development" + soil conditions -> ground displacement). Note Gill and Malamud (2014) did not include air pollution in their original classification.

We included the co-production of multi-hazard interrelationship scenarios and their impacts to expand upon the methodology developed by Gill and Malamud (2014). The multi-hazard impacts shared by participants are summarised into three main themes: cascading impacts, disaggregated impacts, and the disproportionate impact on "marginalised" communities. Participants discussed how cascading impacts can interact dynamically across spatial and temporal scales and contribute to systemic impacts propagating across sectors. This systems thinking mirrors the development of Gill and Malamud's (2014) matrix by Matanó et al. (2022) to include socio-economic impacts. For example, the impact of earthquake or monsoon events on hydropower function and electricity supply has wide-reaching effects across Kathmandu Valley due to load-shedding power cuts. This reduction in energy supply is likely to disproportionally impact urban poor communities due to less reliable electricity connections even before load-shedding activities. Within these communities, the burden of power outages is expected to fall on women and youth, emphasising the importance of a disaggregated approach to multi-hazard impacts (Brown et al., 2019). Participants commented on the relationships between higher vulnerabilities of "marginalised" communities, notably the positive feedback loops between multi-hazard events and increasing informality. Of note is the increase in landslides following the Gorkha earthquake, supported by studies such as Kargel et al. (2015) review of satellite observations, contributing to increased informality within Kathmandu Valley. These observations by participants reflect the informal conditions that many long-term internally displaced people (IDPs) experienced whilst still living in camps and temporary accommodation in the urban periphery many years after the Gorkha earthquake (Titz, 2021).

4.3.2 Impact examples

The impact examples shared by participants on the Padlet page (**Table 4**) can be subdivided into the following themes: cascading impacts, disaggregated impacts, and impacts on "marginalised" communities.

Cascading, or networks of interdependent, impacts may be dynamic and change over space and time (De Brito, 2021). They also occur as part of broader systems that emphasise feedbacks between impacts (Spoon et al., 2020; Hochrainer-Stigler et al., 2023). One participant commented on how the "impacts of [an] earthquake or large monsoon on hydropower function and electricity supply to KTM [Kathmandu], via direct damage to infrastructure (shaking/landslides) or protracted sedimentation, [can] impact upon [the] wider power grid [which] impacts all users of power via load shedding." This observation demonstrates how direct impacts of a hazard event can have broader systemic effects that affect communities across greater spatial and temporal scales than the hazard event itself.

Another theme that emerged in the Padlet pages is the disaggregation of multi-hazard impacts. In this case, we define disaggregated impacts by social group, i.e., gender, age, socio-economic status, disability, etc. One participant noted that we must think beyond direct tangible impacts to consider "multi-hazards affecting land use, increasing inundation and landslides, which disproportionately impact farmers [and] women". Effects such as "assets damaged and or assets los[t] due to these hydro-climatic impacts [which] has [a] direct connection with livelihoods of the people" contributes towards anxiety and a chronic state of emergency experienced by urban poor communities. The consideration of indirect and intangible impacts is necessary when addressing "socio-economic impact[s], gender inequality [and] development challenge[s]".

Considering "marginalised" communities was a closely related theme to disaggregated impacts. Participants emphasised the increased vulnerability of urban poor communities who live in temporary accommodation on riverbanks; "flood has a direct impact on [the] urban poor, mainly those living in temporary shelter[s] built on the bank[s] of Bagmati river. Every year, flood[s] terrif[y] those living in the informal settlements.". Participants also noted the vulnerability of other "marginalised" groups, where "multi-hazard scenarios increase 'uncertainty' which affect primarily migrants and marginalised dwellers" and "migrants who cannot vote in Kathmandu Valley's cities are particularly vulnerable to impacts". One participant commented that following the 2015 Gorkha earthquake, increased landslides on the periphery of and outside Kathmandu Valley contributed to a rise in informality in Kathmandu Valley.

4.4 Single hazard and multi-hazard interrelationship impacts

While we compiled literature on evidence for single hazards and multi-hazard interrelationships influencing Kathmandu Valley, we also noted impacts described. Within the exemplars we collated from blended source types, we found the most detailed descriptions of single hazard (Column 9 in **Supplementary Material A**) and multi-hazard interrelationship (Column 6.1 in **Supplementary Material B**) impacts in academic literature and grey literature (e.g., UNDRR reports). Media and social media (e.g., YouTube videos) also provided informative accounts, but descriptions often described generic and larger spatial impacts rather than event-specific ones. The depth of information on impacts usually reflected the frequency of the hazard and its level of impact. For example, information about the impacts of extreme temperature (cold) events was limited to generic descriptions of environmental and socio-economic consequences due to the rare occurrence of low temperatures in the valley. Most impact information centred on direct quantitative information, such as infrastructure damage, economic losses, injuries and loss of life. Descriptions of ground collapse impacts were limited to general information about fatalities and disruption. Of note was an impact intensity scale developed by the local community in response to Windstorm Parvana in south-central Nepal in March 2021. The classification assessed building and infrastructure damage to determine the storm's intensity as an example of a grassroots-developed impact intensity scale (Gautam, 2020). The limited number of indirect and intangible impacts could be due to sampling bias of the source types used in the study, the sample size of the hazard events impacting Kathmandu Valley, and information accuracy when verification of source types is not possible (Matanó et al., 2022).

When indirect and qualitative impacts of single hazard events were documented, three main themes were common: the disproportionate burden experienced by some social groups (disaggregated impacts) due to variable exposure, vulnerability and anthropogenic factors. For example, following the 2015 Gorkha earthquake, aftershocks (and resulting landslides) contributed towards 2.5-3.5% of the national population entering poverty – equivalent to 700,000 additional poor people (ILO, 2017) – where low caste and poorer communities experienced the greatest severity of impacts due to "marginalised status, limited resources and livelihood options" (UNDRR, 2019). These impacts emphasised the relationship between communities' socio-economic status and vulnerability. The disproportionate burden on some social groups was echoed in the reporting of drought events impacting Kathmandu Valley. Long-term drought in the early 2000s resulted in gendered consequences where missed education significantly affected girls and increased water theft from neighbouring wells and water trenches (IIED, 2010). The impacts of drought, exacerbated by overpopulation and rapid urbanisation, may undermine social cohesion as water shortages promote conflict between communities in the valley in the future (Adhikari, 2019).

Less impact information was documented for multi-hazard events, perhaps since fewer details of multi-hazard interrelationships are recorded across all source types. As a result of the 2015 Gorkha earthquake and aftershocks, over 50% of fatalities were of individuals from "marginalised" communities. Tamang communities experienced disproportionate

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impacts of the event due to "poverty, neglect and outright discrimination" (Magar, 2015). High frequency-magnitude multi-hazard events generally included a greater breadth and depth of impact information as these events have more significant spatial and temporal impacts and are more likely to be documented across source types. For example, storm-triggered flood events in 2019 increased the occurrence of diseases like Dengue fever (Molden and McMahon, 2019). Further storm-triggered floods and landslides in 2021 disproportionately affected urban poor communities owing to the most significant damage occurring in low-lying informal settlements (ReliefWeb, 2021).

4.5 Limitations

We recognise that limitations in the methodology may have altered which hazard events, impacts and multi-hazard scenarios we observed in our results. In this section we highlight the following limitations to encompass the collation of blended sources of evidence and the stakeholder workshop.

Two main factors contributed to uncertainty during the systematic approach to selecting evidence. These include the following:

- We used a *limited number of keywords* during the search process, thus limiting the number of publications returned; alternative keywords would have yielded different results. This limitation includes variations on hazard terms, such that different spatial or temporal terminology versions do not limit the number of returned publications (Taylor et al., 2015).
- We searched for evidence using *English language* databases, search engines and media websites. Solely conducting searches in English reduced the number of publications returned whilst also losing the nuance and context of single hazards and multi-hazard interrelationships described in Nepali language publications (Šakić Trogrlić et al., submitted).

We minimised these limitations by considering efficient and practical solutions for each source of uncertainty. It would be impractical to include a long list of keywords during the search process; instead, we included three to four specific words to target the most relevant publications for each single hazard or multi-hazard interrelationship. For instance, "Kathmandu AND storm* AND flood* AND impact*" identified examples of storm-to-flood hazard sequences without specifying the type of hazard interrelationship, which may have excluded the return of some publications (Taylor et al., 2015). Searching in three reputable online English-language Nepali newspapers reduced the English language limitation. By searching across online newspapers, a greater breadth and depth of sources could be returned than by solely using one newspaper, whilst also returning publications detailing events across greater spatial and temporal scales (De Brito et al., 2021). We focused on publications from 2010 onwards to outline recent hazard events whilst not excluding low probability high impact events. This decision enables exemplars to be viewed in the current context regarding multi-hazard knowledge and approaches to DRR.

The findings from the workshop represent a snapshot of the hazardscape in Kathmandu Valley. They are a product of the perspectives and identities of those present in the discussion and those absent (Leonard et al., 2014). Regarding participants' professional interests, three specialised in the knowledge of multi-hazards from a physical sciences perspective, three in interdisciplinary approaches and one in understanding risk from a social sciences context. Although we approached participants with a range of subject expertise (Matanó et al., 2022), due to availability, there was a bias towards landslide and earthquake hazards, cascades, and impacts, as three of the participants had expertise in these fields. As described in **Sect. 2.4.2** the ratio of Nepali or Nepali-based to British or British-based participants was designed to minimise the effect of power asymmetries within the discussion and create an atmosphere where all participants felt able to share their perspectives (Secor, 2010; Wolf, 2018). Conversely, the gender balance between participants was less representative, despite approaching approximately equal numbers of male and female participants. To minimise this imbalance, we aimed to facilitate the session in a manner that decentred our role as facilitators and limited control of the conversation by one or a few individuals. Our positionalities as researchers may have affected the discussion dynamics, particularly in what information was shared or withheld, how participants described case studies and theoretical examples, and what details they included. By inviting participants with whom we have working connections and partnerships or are within our network as researchers, we hoped to share knowledge built on these sustainable connections and a greater sense of trust (Wilmsen, 2008). The following section examines how we could develop the work of this paper in the future.

4.6 Scalability to other data-scarce urban settings

Building upon previous work (Gill et al., 2020; Matanó et al., 2022; Gustafsson et al., 2023; Šakić Trogrlić et al., submitted), this study has furthered existing methodologies to collate blended sources of evidence of single hazards, multi-hazard interrelationships and their impacts. We demonstrate that it is possible to systematically gather case studies and theoretical examples of multi-hazard events to improve knowledge of hazardscapes in data-scarce urban settings. This challenge is particularly relevant in urban settings in low- to middle-income countries (Osuteye et al., 2017).

With application to Kathmandu Valley, we have developed this methodology to collate single hazard and multi-hazard event data on finer spatial resolutions (e.g., ward level within Kathmandu Valley) and impact data that consider disaggregation by social group (e.g., gender, age, disability). We have achieved this finer spatial resolution and disaggregation of impacts by using a systematic review of blended sources of evidence (academic literature, grey literature, media, databases, and social media) to minimise the effect of data scarcity and provide evidence from various perspectives. The workshop component of the methodology enables stakeholders engaged in DRR work in Kathmandu Valley to co-produce multi-hazard interrelationship scenarios and their impacts. This knowledge generation supplements the blended evidence sources we collated for single hazards and multi-hazard interrelationships and emphasises the most significant scenarios and impacts in the Kathmandu Valley context. These multi-hazard interrelationship scenarios can support dialogue between stakeholders engaged in people centred DRR strategies in the local context. These scenarios can raise awareness in at-risk communities, support risk-sensitive land use planning, and strengthen hazard preparedness and response strategies (Gill et al., 2020).

Applying learnings from the Kathmandu Valley context, this methodology has the scalability to other data-scarce urban settings as it utilises a variety of blended source types given their availability. Once the researcher applies spatial and temporal boundaries to the chosen study area, they can use systematic searches to gather theoretical and case study events across blended source types. Although it may be appropriate to focus on more recent hazard events to capture the current state of the hazardscape, searching across a broader temporal range would enable an analysis of how patterns in multi-hazard events and their impacts change across space and nature of interactions. The researcher should consider what resolution is possible for the urban context chosen and how data scarcity affects which single hazards, multi-hazard interrelationships and impacts are returned in searches (Matanó et al. 2022).

4.7 Future work

In the future, we suggest that researchers engage further with local stakeholders and affected communities to enable the collection of critical insights into their main concerns regarding multi-hazards and DRR strategies. This engagement would support the implementation of the methodology we have outlined in this paper in the Kathmandu Valley context as a pilot for other data-scarce urban areas.

To this end, we included an additional column for hazard impacts in **Supplementary Material B** to allow for further context and insight into the consequences of each exemplar. We included a column for input from stakeholders (**Supplementary Material B** Column 7. *Input from stakeholders*) to assess:

- Is the identified interrelationship relevant for/applicable to Kathmandu Valley?
- Would you classify the identified interrelationship as important for today's Kathmandu Valley?
- Is this interrelationship relevant for future Kathmandu Valley (e.g., will become increasingly important), and should it be considered in urban planning?

We listed a final column for stakeholder prioritisation (**Supplementary Material B** Column 8. *Input from stakeholders – prioritisation*), asking stakeholders to:

- Indicate the most critical hazard interrelationships in today's Kathmandu Valley.
- List hazard interrelationships that you feel will be relevant for Tomorrow's Kathmandu Valley (including the interrelationships which are already relevant today).

Providing an up-to-date summary of single hazards affecting Kathmandu Valley, or with a theoretical chance of occurrence, could give stakeholders a more detailed insight into the natural hazards influencing the valley. These stakeholders include government agencies (e.g., Ministry of Home Affairs – MOHA), non-governmental organisations (e.g., Practical Action Nepal, Lumanti Support Group for Shelter), academia (e.g., Tribhuvan University) and private sector (e.g., Atullya Foundation Pvt. Ltd.) working on inclusive approaches to DRR in Kathmandu Valley and Nepal more widely.

5 Conclusions

This paper has detailed the systematic and evidenced process of collating exemplars of single hazards and multi-hazard interrelationships in a data-scarce urban area with application to Kathmandu Valley. We supplemented these exemplars with the perspectives of stakeholders engaged in DRR in the Kathmandu Valley context. Using blended evidence types captures multi-hazard interrelationship scenarios and their impacts in greater depth than using fewer source types (Neri et al., 2008; Gill et al., 2020; Taylor et al., 2020). Data-scarce urban areas in the "Global South" represent an important research focus for deepening understanding of multi-hazard interrelationship scenarios and impacts. High vulnerabilities of urban poor communities, combined with rapidly increasing population growth and exposure to complex multi-hazard interactions (Dodman et al., 2022), present a significant challenge to effective community led DRR strategies. Improved knowledge of multi-hazard interactions and cascades in Kathmandu Valley would enable a more holistic approach to DRR from various stakeholders. We argue that this paper promotes using blended evidence types in collating single and multi-hazard event information in data-scarce urban settings. It demonstrates the importance of disaggregated impact information in supporting communities to respond to hazard events and increase their resilience to future events. We suggest that the methodology presented in this paper could contribute towards resolving some of these data obstacles across urban data-scarce urban regions (UNDRR, 2023).

Across the source types we searched, single hazards were more common (i.e., academic literature, grey literature, media, databases, and social media), with greater detail of anthropogenic processes and impacts. The 58 single hazard sources we selected from the literature search evidenced 21 single hazards that might influence Kathmandu Valley. Discussions with participants supported the single hazards documented in the blended source types. In contrast, searching for evidence of triggering and increased probability multi-hazard interrelationships in Kathmandu Valley was challenging across all source types. We selected 21 multi-hazard interrelationship sources which evidenced 12 specific multi-hazard interrelationships that might influence Kathmandu Valley, out of 83 that we propose as having a theoretical possibility of affecting the valley. Participants confirmed the challenge of documenting complex multi-hazard interrelationships by predominantly describing simpler primary to secondary hazard interactions. The discussion also developed the process of considering multi-hazard impacts in Kathmandu Valley, specifically knowledge of cascading impacts, disaggregated impacts by social group and the disproportionate impact borne by "marginalised" communities (Brown et al., 2019; Dodman et al., 2022).

These single hazard and multi-hazard interrelationship databases can assess which hazards and hazard interactions are most significant in Kathmandu Valley and how this may change. Local stakeholders can integrate a better understanding of the hazardscape, and resulting impacts, in Kathmandu Valley into more holistic approaches towards multi-hazard DRR. We suggest that this paper's findings will contribute to developing multi-hazard interrelationship scenarios as part of the objectives of the midterm review of the Sendai Framework and other national and international research priorities.

Data availability

The blended sources used to collate the single hazards and multi-hazard interrelationships in Kathmandu Valley are available in **Supplementary Material A. Kathmandu Valley Single Hazard Database** and **Supplementary Material B. Kathmandu Valley Multi-Hazard Interrelationship Database.**

Author contribution:

HET, JCG, RST and BDM conceptualised the research and developed the methodology. HET analysed the data, undertook the investigation, visualised the results and wrote the manuscript draft. JCG, RST, FET and BDM supervised the research. All co-authors reviewed and edited the manuscript.

Competing interests:

Two authors (BDM and RST) are members of the editorial board of *Natural Hazards and Earth System Sciences*.

Disclaimer

We have not published any part of this paper elsewhere, nor is this paper or any component of it under consideration by any other journal.

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