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Multi-Hazard Interrelationships and Risk Scenarios in Urban Areas: A Case of Nairobi and Istanbul

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Key Points:

- Using Nairobi and Istanbul, we introduce a framework for analyzing multi-hazard interrelationships in low- and medium-income cities
- A systematic review of 135 sources finds 19 and 23 hazard types and 88 and 105 hazard interrelationships in Nairobi and Istanbul, respectively
- Workshops and interviews identify risk scenarios, governance challenges, and opportunities for multi-hazard integration in urban policies

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Abstract This paper introduces a methodology for characterizing the breadth of natural hazard types, hazard interrelationships, and risk scenarios in Global South urban areas, focusing on Nairobi, Kenya, and Istanbul, Türkiye. Our approach involves (a) a comprehensive characterization of multi-hazards and their interrelationships in an urban setting, (b) collaborative development of relevant multi-hazard scenarios with local disaster risk reduction (DRR) stakeholders, and (c) analysis of the potential for integrating these scenarios into urban DRR efforts. Using a critical review of 135 sources (academic and gray literature, databases, online, and social media), we identify 19 natural hazard types that might influence Nairobi and 23 in Istanbul. We further identified in Nairobi 88 and Istanbul 105 hazard interrelationship pairs (e.g., an earthquake triggering landslides) out of a possible 576 interrelationships. These findings are cataloged in an extensive database, which informs the creation of multi-hazard risk scenario exemplars for each city. These exemplars are refined through stakeholder engagement, involving four workshops (47 participants) and nine semi-structured interviews with local DRR stakeholders. Despite the identified benefits, this engagement reveals a significant gap in integrating multi-hazards into current urban policy and practice. Governance challenges are highlighted as a key barrier, but opportunities for better integration are also identified, including evolving policies and growing awareness among urban actors. Our approach, particularly relevant in data-scarce urban areas of low- and middle-income countries, provides a framework for exploring multi-hazard issues in various urban contexts.

Plain Language Summary Our study sought to understand the breadth of natural hazards an urban area in the Global South might face, how the hazards are interrelated (e.g., an earthquake can trigger landslides), and typical risk scenarios that matter to local experts. We applied our methodology to Nairobi and Istanbul to assess how considering multiple hazards could enhance disaster risk reduction (DRR) efforts. We systematically reviewed 135 information sources, including gray and peer-reviewed literature and online and social media. We found 19 natural hazard types could influence Nairobi, while Istanbul faces 23. These hazards showed numerous interactions, with 88 in Nairobi and 105 in Istanbul. Subsequently, we held workshops and interviews with local DRR stakeholders in both cities to co-designed multi-hazard risk scenarios. Practitioner stakeholders in Nairobi and Istanbul emphasized that considering these interrelationships helped create comprehensive risk scenarios and improved planning for addressing multiple hazards concurrently, a crucial aspect of urban safety and preparedness. They noted that current city policies and practices often overlooked this approach, primarily due to risk management and governance issues; for example, siloed approaches to DRR resulting in disjointed implementation and planning, and a lack of coordination and communication among actors. Our research framework may assist other urban areas, particularly those in developing countries with limited data, in comprehending and preparing for the complex challenges posed by various natural hazards.

1. Introduction

In February 2023, Türkiye and Syria were hit by sequential earthquakes of magnitude 7.8 and 7.5, with impacts intensified by extreme cold (BBC, 2023), landslides (Başer, 2023), and floods (Hammoud & Gharaibi, 2023). These events illustrate the complexity of natural hazards, showing that locations often face multiple,

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interrelated hazards over various scales (De Angeli et al., 2022; Tilloy et al., 2019). The United Nations Office for Disaster Risk Reduction (UNDRR) defines multi-hazards as "(a) the selection of multiple major hazards that the country faces, and (b) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects" (UNDRR, 2016). This paper introduces a methodology for characterizing the breadth of natural hazard types, multi-hazard interrelationships and multi-hazard scenarios in the context of urban areas, featuring case studies in Nairobi and Istanbul. The rest of this introduction gives a background to multi-hazards, the urban area context and study motivation.

Multi-hazard events often have more severe impacts than single-hazard events and present challenges for traditional risk assessment and management (Gustafsson et al., 2023; Kappes et al., 2012; Matanó et al., 2022; Šakić Trogrlić et al., 2022; Schlumberger et al., 2022; Thaler et al., 2023; Ward et al., 2022). Natural hazards can interrelate in various ways, as discussed extensively in the literature (Ciurean et al., 2018; De Angeli et al., 2022; Gill & Malamud, 2014; Gill et al., 2022; Hochrainer-Stigler et al., 2023; Tilloy et al., 2019). The main types of hazard interrelationships include:

- *Triggering:* one hazard directly causes one or more primary or secondary hazards, where secondary hazards might be identical or different from a primary hazard (Gill & Malamud, 2014; Tilloy et al., 2019). For instance, an earthquake triggers a landslide, or an earthquake triggers further earthquakes.
- *Amplification (an increasing or decreasing probability):* a hazard changes environmental factors, affecting the likelihood of another hazard (Gill & Malamud, 2014); for example, a forest fire increasing debris flow risk.
- *Compound hazards:* different hazards are part of the same primary event or a large-scale process, such as sea surges and river flooding (Tilloy et al., 2019).
- *Coincident hazards that are independent*: the influence of these hazards overlap in space and time but have no underlying dependence mechanisms (Tilloy et al., 2019); for example, an earthquake and hailstorm influencing simultaneously the same spatial region and temporal period.
- *Consecutive hazards:* successive hazards with overlapping impacts, such as an earthquake followed months later by a flood (de Ruiter et al., 2020).

This paper examines multi-hazards and their interrelationships in urban settings, using Nairobi and Istanbul as case studies. Urban areas, often in hazardous zones such as coastal regions and floodplains, are hotspots for disaster risks due to dense populations, infrastructure, and economic activities (Guerreiro et al., 2018; Rosenzweig & Solecki, 2014). Factors such as rapid urban growth, increasing populations, poor planning, and climate change impacts heighten the risk and vulnerability to natural hazards (Cremen et al., 2023; Jenkins et al., 2022). Recent studies highlight the need for risk-informed urban development to address multiple natural hazards (Bathrellos et al., 2017; Cremen et al., 2022a, 2023; Galasso et al., 2021; Jenkins et al., 2022), as different hazards often occur in relatively small areas (Johnson et al., 2016).

While many studies focus on individual natural hazards in urban areas, such as floods or earthquakes (Cremen et al., 2022a; Hallegatte et al., 2013), they often overlook the interrelationships between different or the same hazard types. Studies that do consider multiple hazards typically do not explore the interrelationships between different hazards (Guerreiro et al., 2018; Pourghasemi et al., 2020; Skilodimou et al., 2019), with some exceptions, for instance, compound flood event research (e.g., Q. Liu et al., 2022; van Berchum et al., 2020). In reality, urban areas face a complex mix of interrelated hazards.

While multi-hazard research has considerably evolved since 2010, research on multi-hazards and their interconnections in urban areas of low- and middle-income countries is scarce. However, these countries are expected to see 95% of future urban growth (UN Habitat, 2022). They face specific challenges, including:

- Rapid urban changes, including infrastructure and governance development, lead to dynamic risk landscapes and increased risk exposure (Dodman et al., 2017; Rusk et al., 2022; Sanderson et al., 2022).
- High levels of informal settlements increase hazard exposure and vulnerability (Fraser et al., 2017; Sandoval & Sarmiento, 2020).
- A lack of data on past events, especially low-magnitude high-frequency events, hinders risk analysis and decision-making (Osuteye et al., 2017).

Considering these challenges in urban areas in low- and middle-income countries, the following are three aims of this paper:

- To develop an approach for surveying the breadth of single hazard types and their multi-hazard interrelationships in these often data-poor urban areas, underpinned by a systematic review of a diverse range of evidence (e.g., academic and gray literature, media articles, databases, social media).
- To co-develop multi-hazard scenarios of interest for local DRR stakeholders in urban areas through workshops and interviews.
- To identify potential uses, challenges, and opportunities for mainstreaming multi-hazard thinking into DRR efforts in urban areas in low- and middle-income countries.

We use Nairobi (Kenya) and Istanbul (Türkiye) as the basis for analysis because they exemplify urban areas in low- and middle-income countries with a range of natural hazards and rapid urban development challenges. Nairobi City, Kenya's capital, has about 4.8 million people (estimated for 2024) over 696 km^2 (KNBS, 2019). Nairobi predominantly houses its population in informal settlements (60%–70%) and faces multiple hazards and unsafe conditions (Corburn et al., 2022; McDermott et al., 2022). Istanbul, Türkiye's largest city, had about 15.9 million people (in 2022) living over an area of 5,340 km^2 (Turkish Statistical Institute, 2023). Istanbul confronts major hazards such as earthquakes and floods, compounded by significant migration, both internal and international, increasing vulnerability, especially among the poorest urban residents (Biehl, 2020; Kalaycıoğlu et al., 2023; Öztürk et al., 2018). Both cities are part of the GCRF (Global Challenges Research Fund) Tomorrow's Cities Hub (https://tomorrowscities.org/), under which part of this research has been conducted. The Hub aims to reduce disaster risks in future development by establishing a decision-support platform for risk-informed urban development (Cremen et al., 2023).

This paper is organized as follows. Section 2 details our methodological approach, including systematic evidence-gathering based on a blend of various source types and stakeholder engagement through workshops and interviews. Section 3 presents the main results, Section 4 discusses the results, and Section 5 presents conclusions. Accompanying the paper is an extensive open-access Excel *Nairobi and Istanbul Multi-Hazard Interrelationships Database* (Šakić Trogrlić et al., 2024).

2. Materials and Methods

To uncover evidence on single hazard types and their interrelationships and investigate the practical implementation of multi-hazard thinking, we employ a mixed-method approach, presented in Figure 1. This approach involves systematic reviews of diverse evidence sources paired with stakeholder engagement, including workshops and key informant interviews.

Our methodology builds on Gill et al. (2020) for synthesizing natural-hazard interrelationships in Guatemala at national and sub-national levels. For evidence searches, we followed De Angeli et al. (2022) and Cremen et al. (2022b) in seeking a representative view of literature, focusing on exemplars as opposed to providing a review of all literature, and based on specific search terms and inclusion and exclusion criteria in line with the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) approach (Page et al., 2021). In line with the systematic review approach of Boaz et al. (2002), we aimed to (a) answer specific research questions (i.e., "What are the natural hazard types that influence or have a potential to influence Nairobi or Istanbul?," "What are interrelationships between natural hazards in Nairobi and Istanbul?"), (b) select a representative sample of sources. The methodology of Gill et al. (2020) was enhanced by localizing hazard interrelationships to the urban scale and involving stakeholders in workshops and interviews to discuss integrating multi-hazard approaches into policy and practice. For this study, we mainly consider natural hazards. For a comprehensive overview of natural hazard typologies, see UNDRR & ISC (2021).

In this paper, we refer to our database built using the methodology described below and the results presented in Section 3. This *Nairobi and Istanbul Multi-Hazard Interrelationships Database* (Šakić Trogrlić et al., 2024) consists of the following eight tabs (in brackets the number of rows [R] × columns [C] of information):

A. Single Hazard Evidence Nairobi (87R × 16C)
B. Single Hazard Evidence Istanbul (68R × 11C)
C. Hazard Interrelationships Nairobi (118R × 14C)

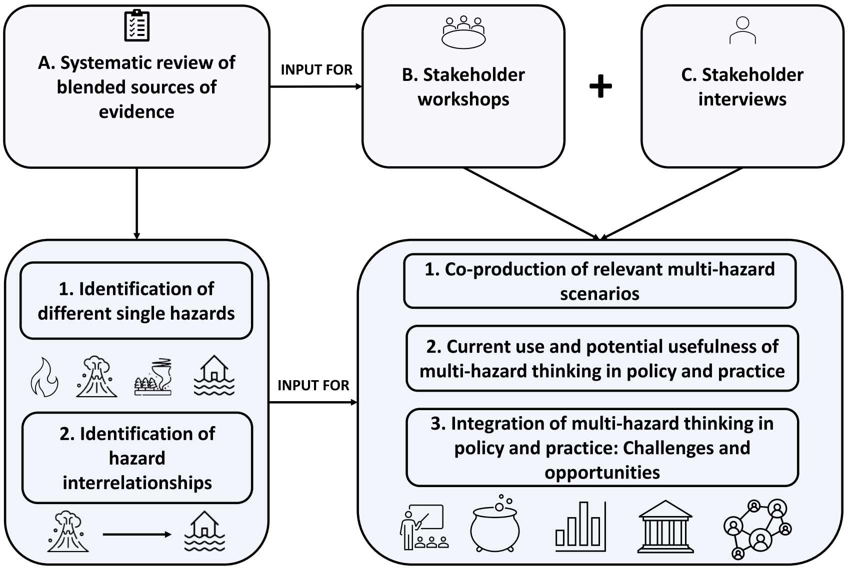

Figure 1. The flow of the methodological approach used in this study to investigate multi-hazards and their interrelationships in urban areas, with case studies in Nairobi and Istanbul. We start (box A) with an extensive review of 135 unique blended sources of evidence that sets the baseline for the research and is made available as an open-access database (Šakić Trogrlić et al., 2024). Thereafter, stakeholder workshops (box B, two each in Nairobi and Istanbul; total 47 participants) provide more detailed information about the hazard context, multi-hazard scenarios of interest, and stakeholder views on different aspects of multi-hazards in practice. Finally, key informant interviews (box C, six in Nairobi, three in Istanbul) provide further contextual details and an in-depth perspective. (Icons used in the creation of this figure courtesy of www.freepik.com).

D. Hazard Interrelationships Istanbul (122R × 13C)
E. Definitions (Evidence Types) (7 definitions)
F. Definitions (Hazards) (31R × 5C)
G. Definitions (Hazard Relations) (3 definitions)
H. References

2.1. Developing an Overview of Single Hazard Types

For a comprehensive view of the breadth of single hazard types that might influence urban areas, we used a slightly modified classification of natural hazards from that of Gill and Malamud (2014) (see Figure 2). We maintained their six hazard groups (geophysical, hydrological, shallow Earth processes, atmospheric, biophysical, space hazards). However, whereas they had 21 hazard types, we added three more (fog, urban fire, seiche) to arrive at the 24 hazard types we used for classifying hazards in Nairobi and Istanbul. These additions were based on internal discussions with co-authors in Nairobi and Istanbul and discussions with DRR stakeholders from both urban areas. Except for urban fire, all of the hazard types given in Figure 2 are "natural" hazards, although many others are amplified by anthropogenic processes (e.g., landslides, floods, ground collapse). Tab F of our database (Šakić Trogrlić et al., 2024) provides a detailed description of hazard definitions and hazard component processes.

For each of the single natural hazards shown in Figure 2, we searched diverse evidence types (set out below) for evidence of either past occurrence or influence on Nairobi/Istanbul or potential to influence Nairobi/Istanbul. We used simple Boolean searches with keywords in Google, Google Scholar and YouTube. Keywords included Nairobi, Kenya, Istanbul, Turkey, and hazards from the list given in Figure 2 (e.g., Nairobi AND flood*, Kenya AND earthquake*, Istanbul AND tsunami*, Turkey AND earthquake*), with * representing one or more wildcard characters (e.g., s). After getting the search results back, we chose relevant exemplars of evidence for each of the hazards, using diverse types of evidence (six examples shown in Figure 3), including the following (see also Tab E of our database, Šakić Trogrlić et al., 2024):

- *Academic* (peer-reviewed academic work including postgraduate theses);
- *Gray literature* (non-peer-reviewed material, including reports from intergovernmental NGOs, organizations, think-tanks, universities, and other written material such as PowerPoint Presentations);

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KEY		
HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche	AV
HYDROLOGICAL	Flood	FL
	Seiche	SE
	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

Figure 2. Classification of six hazard groups and 24 single hazard types used in our hazard analyses (modified from Gill & Malamud, 2014).

- *Online Media* (material published in newspapers available online and other online material such as webpages of TV broadcasters and blogs);
- *Online Databases* (material relevant to disasters, e.g., EM-DAT, CRED/UCLouvain, 2023 and UNDRR DesInventar Sendai, UNDRR, 2023);
- *Social media* (photo and video materials from social media platforms, e.g. YouTube, X).

Collated evidence for single hazard types occurring in each city was included in our *Nairobi and Istanbul Multi-Hazard Interrelationships Database* (Šakić Trogrlić et al., 2024), with different sheets for Nairobi (Tab A) and Istanbul (Tab B). Each row in the database presents a source of evidence of a single hazard influencing Nairobi or Istanbul. We compiled multiple evidence sources for many of the hazard types, each on its own row. In columns, we describe the evidence through various qualifiers, including the following: the hazard type, source information and URL link, source content, hazard interrelationships and anthropogenic influences, video evidence, and source reflections. An example of the database for the Nairobi "Single" Hazards sheet (Tab A) is presented in Figure 4.

2.2. Developing an Overview of Hazard Interrelationships

After identifying 24 single hazard types of interest (Figure 2), the next step is to identify possible hazard interrelationships between these hazard types, looking at each possible pair of hazard type combinations (e.g., earthquake → earthquake, earthquake → tsunami, earthquake → volcanic eruption). Gill and Malamud (2014) developed a visualization overview of hazard interrelationships globally using a hazard interaction 21 cell × 21 cell matrix (a total of 441 cells). We adapted their visualization methodology (with the addition of other single hazard types as described in Section 2.1), resulting in 24 cell × 24 cell matrices (a total of 576 cells) for Istanbul and Nairobi (described and presented in detail in Section 3.2).

Similar to Gill and Malamud (2014), we focused our overview on two types of interrelationships, namely triggering and increasing probability (amplification) interrelationships (defined in Section 1) between potential pairs of hazard types. We examined blended sources of evidence (Section 2.1) for hazard interrelationships that occurred or have influenced Nairobi and Istanbul in the past or might have the potential to influence these urban areas in the future. Using primarily Google and Google Scholar, our search was again conducted using a simple Boolean search with keywords (e.g., flood* AND landslide* AND Kenya, tsunami AND earthquake* AND Turkey). For keywords, we used a combination of hazards described as having an interaction in the Gill and Malamud (2014) matrix and explored interrelationships, including newly added hazards (described in Section 2.1). However, the evidence search was not as straightforward as with single hazards, as reports explicitly focusing on hazard interrelationships were rare. Instead, the secondary hazard was often mentioned as a side note to reports on single hazards. As for the single hazards approach outlined in Section 2.1, we chose relevant examples of evidence for each hazard interrelationship upon getting the search results back.

As in our methodology for single hazards, we collate the evidence of hazard interrelationships in our database (Šakić Trogrlić et al., 2024) for Nairobi (Tab C) and Istanbul (Tab D). Each row in the databases presents a source of evidence of a hazard interrelationship in Nairobi or Istanbul. In columns, we describe the evidence through various qualifiers, including the following: primary hazard (24 hazards from Figure 2), secondary hazard (where applicable, the 24 hazards from Figure 2), the generic description of hazard interrelationship mechanisms, whether the relationship is triggered or increased probability or both, source information and link, and source content (e.g., interrelationship type, description, and hazard sequence).

Figure 3. Examples of six sources (out of 62) used to compile our Nairobi single-hazard overview. Details of all 62 sources are in our *Nairobi and Istanbul Multi-Hazard Interrelationships Database* (Šakić Trogrlić et al., 2024). Subfigures from: (a) Ngau and Boit (2020); (b) Khan (2012); (c) Mulligan et al. (2017); (d) NTV Kenya (2019); (e) Citizen YV Kenya (2019); (f) Mulwa et al. (2014).

2.3. Stakeholder Engagement: Workshop and Key Informant Interviews

Our systematic review helped map single hazard types in target cities and understand hazard interrelationships using a visualization matrix. Additionally, we aimed to grasp multi-hazard integration in policy and practice and gather stakeholder feedback on hazard scenarios. We conducted workshops and interviews in Nairobi and Istanbul to collect further data:

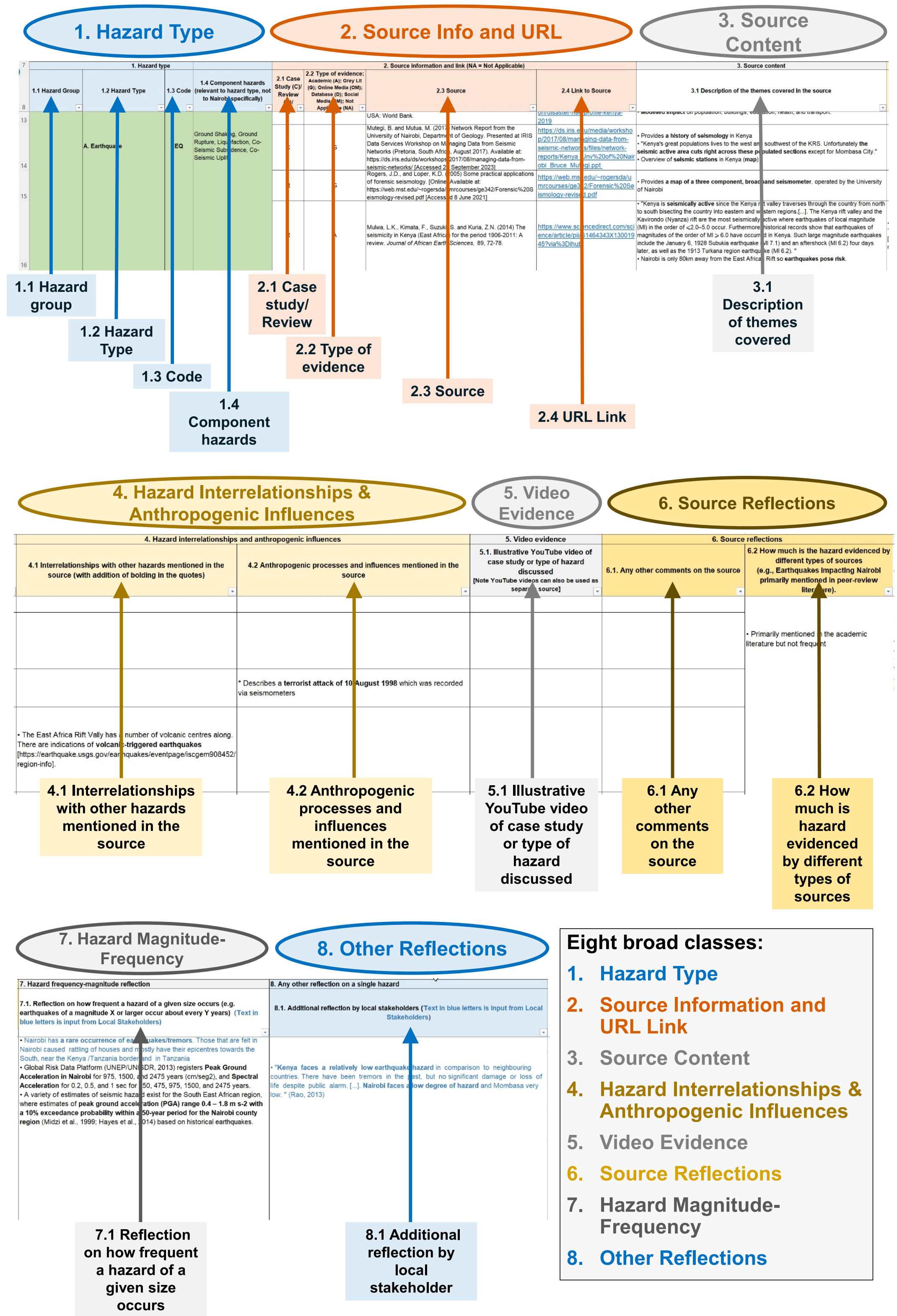

Figure 4. Illustration of our systematic presentation of evidence for "single" natural hazards that might influence Nairobi (rows 8 and 13–16, Tab A, in our *Nairobi and Istanbul Multi-Hazard Interrelationships Database*, Šakić Trogrlić et al., 2024).

- In Nairobi, data were gathered from two 2-hr workshops (12 and 9 participants) in May 2021 and six key informant interviews in July 2021.
- In Istanbul, data collection involved two 3-hr workshops (13 participants each) and three key informant interviews in October 2021.

The workshop and interviews were recorded and transcribed. This study has been conducted under ethical approval obtained from King's College London (MRA-19/20-19713). All participants of the workshops and the interviews were informed of the purpose of their participation and how the data, including their personal data, would be used and protected.

The workshops were structured as facilitated discussions, incorporating presentations, interactive tools (Padlet and Google Docs), breakout groups, and plenary sessions. The key objectives were:

- Co-producing multi-hazard scenarios: Stakeholders from Nairobi and Istanbul developed and characterized relevant multi-hazard scenarios for their cities. Given the research's alignment with the Tomorrow's Cities GCRF project and based on initial discussions with the project teams, the special focus for Nairobi was on flooding and urban fire, and for Istanbul, on flooding and earthquakes.
- Discussing the dynamic nature of exposure and vulnerability during multi-hazard scenarios in both cities.
- Exploring the usefulness of multi-hazard scenarios for different DRR stakeholders.
- Discussing challenges and opportunities for integrating multi-hazards and scenarios into policy and practice in Nairobi and Istanbul.

Stakeholders involved in the workshops represented a breadth of organizations involved in DRR in the cities:

- In Nairobi, these organizations included government agencies, non-governmental organizations focused on development work and research and advocacy, humanitarian agencies, and representatives of academia.
- In Istanbul, most participants were from different government agencies (e.g., urban planning, earthquakes) and representatives of academia.

The authors selected practitioner stakeholders for the Istanbul and Nairobi workshops who have local knowledge of the institutional mapping of hazards and risks in each city and a rich understanding of the local disaster risk management (DRM) system. Furthermore, we selected a mixture of individuals regarding their hazard focus and organization type (i.e., research, government, NGOs).

After the workshops, key informant interviews were organized. Interviews can provide rich insights and authentic accounts of participants' experiences (Flick, 2018). This study used key informant semi-structured interviews due to their flexibility since they allow the interviewer to ask additional questions and probe for clarification, thus obtaining potential further insights (Bryman, 2012).

Key informants for semi-structured interviews were identified in the workshops for follow-up conversations to supplement the narratives from the desk review and workshops, as these informants had particularly rich insights on the topic. Each interview had a duration of 45–60 min. Similar to the workshops, the interviews focused on the following topics:

- Expanded multi-hazard scenarios and possible evidence sources of previous multi-hazard events in Nairobi and Istanbul.
- The practicalities of integrating multi-hazard thinking and scenarios in DRR in Nairobi and Istanbul, focusing on the opportunities, challenges, and a way forward.

2.4. Qualitative Data Analysis

Workshops and semi-structured interviews resulted in a rich qualitative data set, which we analyzed using thematic analysis. Thematic analysis is a commonly used method in analyzing qualitative data based on identifying, analyzing, and reporting themes within data sets (Braun & Clarke, 2006).

We used NVivo, a qualitative data software produced by Lumivero, for the thematic analysis. We chose NVivo as it allowed for an easier overview of the data, coding process, and manipulation of sub-themes and themes. Paulus and Lester (2020) note that using software to analyze qualitative data can lead to more efficient and effective analysis, especially of larger samples.

We imported workshop and interview transcripts to NVivo. In NVivo, we (a) assigned codes to pieces of text, including words, phrases, sentences, and paragraphs; (b) merged codes into sub-themes and sub-themes into themes. For our thematic analysis, we used the six stages of thematic analysis as outlined by Nowell et al. (2017): (a) familiarizing ourselves with the data (i.e., transcripts), (b) generating initial codes, (c) searching for themes, (d) reviewing themes, (e) defining and naming themes, and (f) producing the report (i.e., writing up the findings). The main themes and sub-themes from our analysis are presented in the results (Section 3.3).

3. Results

3.1. Overview of Single Hazard Types in Nairobi and Istanbul

The results of our overview of single natural hazards that might influence Nairobi or Istanbul are as follows:

- In Nairobi, based on 62 sources of evidence, we identified 19 single hazard types (out of 24) that have or might influence Nairobi. These include all hazards in Figure 2 except for snow avalanches, tsunamis, snowstorms, seiche, and tornadoes.
- In Istanbul, based on 47 sources of evidence, we identified 23 single hazard types (out of 24) that have or might influence Istanbul. These include all hazards in Figure 2 except for snow avalanches.

Our detailed results are given in Tabs A and B of our *Nairobi and Istanbul Multi-Hazard Interrelationships Database* (Šakić Trogrlić et al., 2024). Our findings indicate that both Nairobi and Istanbul experience a breadth of natural hazards across all different hazard groups.

Some of the single hazard types found that have or might influence Nairobi or Istanbul (e.g., floods, urban fires, and landslides) originate within cities, while other single hazards occur on a different spatial scale or outside of cities but have a clear impact or influence on the city. For example, in Nairobi, floods, urban fires, and landslides can originate within the urban area. On the other hand, Ndege (2017) describes how the 2017 drought in Kenya resulted in low water levels in the Ndakaini dam (located 50 km outside of Nairobi), resulting in drought-induced water shortage in Nairobi. Furthermore, there are documented instances of ground rupture outside of Nairobi impacting transportation to and from Nairobi (Jacobson, 2018). In Istanbul, while there are no nearby volcanoes, ash from Italian volcanoes has been shown to affect air quality and aviation (Folch & Sulpizio, 2010; Sulpizio et al., 2012).

We have also included natural hazards where we did not find an evidence source for that hazard having previously influenced the urban area (i.e., a case study), but where that hazard might potentially (or theoretically) influence the urban area. For example, if volcanoes in the vicinity of Nairobi were to erupt, there is a potential volcanic impact on Nairobi based on models (GFDRR, 2019). Similarly, according to Campos Garcia and Newman (2018), there is a potential for a high impact on Nairobi from medium-magnitude earthquakes due to the high physical vulnerability of informal housing and non-engineered structures and future exposure change due to population growth.

3.2. Overview of Hazard Interrelationships

After identifying all single hazard types that have or might influence Nairobi ($n = 19$) and Istanbul ($n = 23$), we used secondary data sources to identify all possible hazard interrelationships between these single hazards. These are divided into triggering and increased probability relationships, for example:

- [Triggering interrelationship]
  - Ngau and Boit (2020) explain how urban fires often trigger further urban fires in Nairobi's informal settlements.
  - Altinok and Ersoy (2000) reviewed tsunamis in Türkiye and found evidence that earthquake-triggered tsunamis occurred near Istanbul in 1509, 1894, 1963, and 1999.
- [Increased probability interrelationship]
  - Kenya's disaster risk profile (GFDRR, 2019) shows how volcanic activity could result in ashfall reaching Nairobi, thus potentially increasing the probability of flooding.
  - For Istanbul, Tilev-Tanriover and Kahraman (2015) report how storms increase the probability of lightning and associated injuries, especially in highly densely populated areas such as Istanbul.

Our detailed findings are given in Tabs C and D of our hazards database (Šakić Trogrlić et al., 2024). Out of a potential 576 interrelationships (24 cell × 24 cell matrix), in Nairobi, 88 interrelationships were identified (18 triggered, 20 increased probability, 50 both), while for Istanbul, 105 interrelationships were identified (24 triggered, 21 increased probability, 60 both). From these data, we present an overview in Figure 5 of the hazard interrelationships found in Nairobi and Istanbul using Gill and Malamud's (2014) matrix visualization methodology.

We identify both theoretically possible interrelationships (using Gill & Malamud, 2014 as a first step) and those for which we found evidence that they have influenced Nairobi and Istanbul. For instance, Gill and Malamud (2014) identify that an earthquake can trigger volcanic activity, but we did not find evidence for this having influenced Nairobi; however, the interrelationship was still included as it can theoretically influence Nairobi (or has already appeared, but we found no evidence for it through our review of evidence).

In Nairobi, we found direct evidence for 16 of the 88 identified hazard interrelationships (using 25 sources). The interrelationships for which we found evidence include case examples from Nairobi and sources that indicated a possibility of a specific hazard interrelationship occurring in Nairobi. For instance, while Zhou et al. (2020) show how rainfall generally increases the likelihood of landslides in Kenya (by inference, in Nairobi as well), Khan (2012) reports on an incident from Mathare (an informal settlement within Nairobi), where rainfall triggered a rockfall leading to severe impacts, including reported casualties. In Istanbul, we found direct evidence for 25 of the 105 identified hazards interrelationships (using 21 different sources). Examples include lightning-causing wildfires (Senturk, 2018) and modeling that suggests landslide-triggered tsunamis, which could cause significant damage (Hébert et al., 2005). The hazard interrelationship matrices for both cities help represent multi-hazard scenarios or networks of hazard interconnections (Gill & Malamud, 2016).

The matrices for Nairobi and Istanbul differ in the number of identified interrelationships due to a different number set of single hazard that have or might influence cities (19 for Nairobi and 23 for Istanbul) and the different geographic settings where some interrelationships were possible in one urban area but not in the other area. The different settings resulted in a distinct set of potential hazard interrelationships in Istanbul compared to Nairobi.

The hazard interrelationship matrices (Figure 5) were used to generate scenario visualizations for our workshops and interviews to facilitate discussion and generate further co-developed scenario examples. Two examples of hazard cascade scenarios are given in Figure 6. While hazard interrelationship matrices offer a blueprint from which many scenarios could be generated based on the collected evidence (e.g., Figure 6), in this work, scenarios were also created by stakeholders during workshops, as described in Section 3.3.

3.3. Results of Stakeholder Engagement in Nairobi and Istanbul

As explained in Section 2.3, we engaged with stakeholders in Nairobi and Istanbul through workshops and interviews. In this section, we present the outcomes of thematic analysis of this stakeholder engagement: example multi-hazard scenarios identified by stakeholders (Section 3.3.1), benefits of integrating multi-hazard in DRR (Section 3.3.2) and perceived challenges and opportunities for the use of multi-hazard thinking and scenarios (Section 3.3.3). These findings are then discussed in Section 4.

3.3.1. Example Multi-Hazard Scenarios Identified by Stakeholders

During stakeholder engagement, particularly in workshops, participants in Nairobi and Istanbul were asked to create multi-hazard scenarios relevant for future consideration. Example scenarios (Figure 6) created from the Nairobi and Istanbul hazard interrelationship matrices (Figure 5) were used at the beginning of the workshop to explain the concept of multi-hazards and prompt participants to think about those scenarios relevant to their context. The focus on the future was due to the Tomorrow's Cities research project, which focused on risk reduction in urban areas in the context of future urban development. Table 1 showcases 41 multi-hazard scenarios identified from these activities (21 for Nairobi, 20 for Istanbul) that participants deemed important for guiding future urban development. Participants initially focused on flooding and urban fires in Nairobi and flooding and earthquakes in Istanbul, but other hazard types (and elements of risk, such as hazard frequency and magnitude,

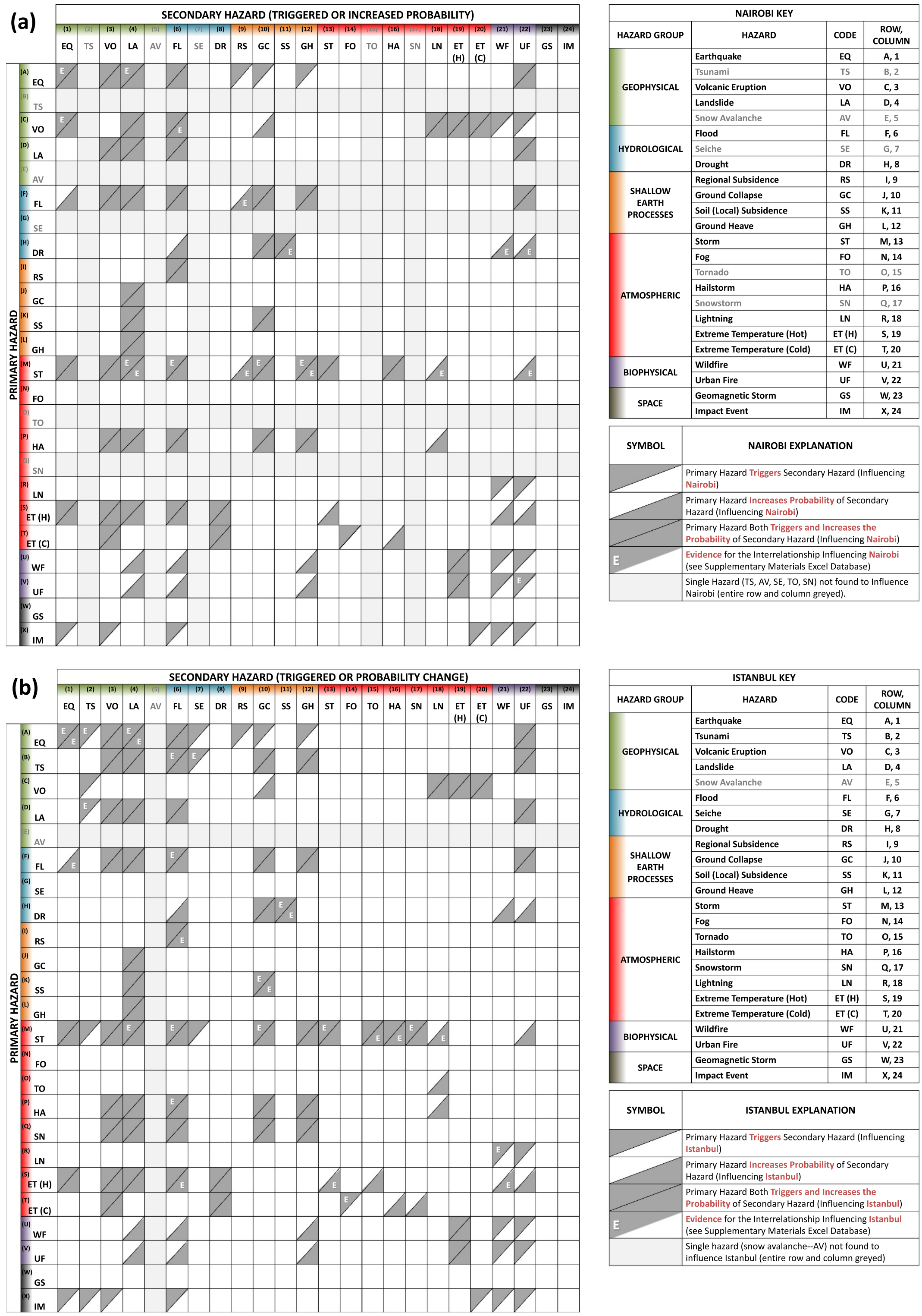

Figure 5. Identification of theoretical and evidenced hazard interrelationships in (a) Nairobi and (b) Istanbul (using visualization methodology from Gill & Malamud, 2014). A 24 cell × 24 cell matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis. Hazards are coded as explained in the key. This matrix shows cases where a primary hazard could trigger (upper-left triangle shaded) or increase the probability (bottom-right triangle shaded) of a secondary hazard, thus influencing Nairobi or Istanbul. Cells with uppercase white letter E indicate that the evidence was found for the hazard interrelationship influencing Nairobi or Istanbul. Other interrelationships (shaded triangles without an E) are theoretical and largely based on the original interaction matrix by Gill and Malamud (2014), except for seiche, fog, and urban fire, as detailed in the text. Entire rows or columns shaded in gray refer to hazard types that do not influence that city. For the detailed data underlying the matrices, see our *Nairobi and Istanbul Multi-Hazard Interrelationships Database* (Šakić Trogrlić et al., 2024) and Section 2 of this paper.

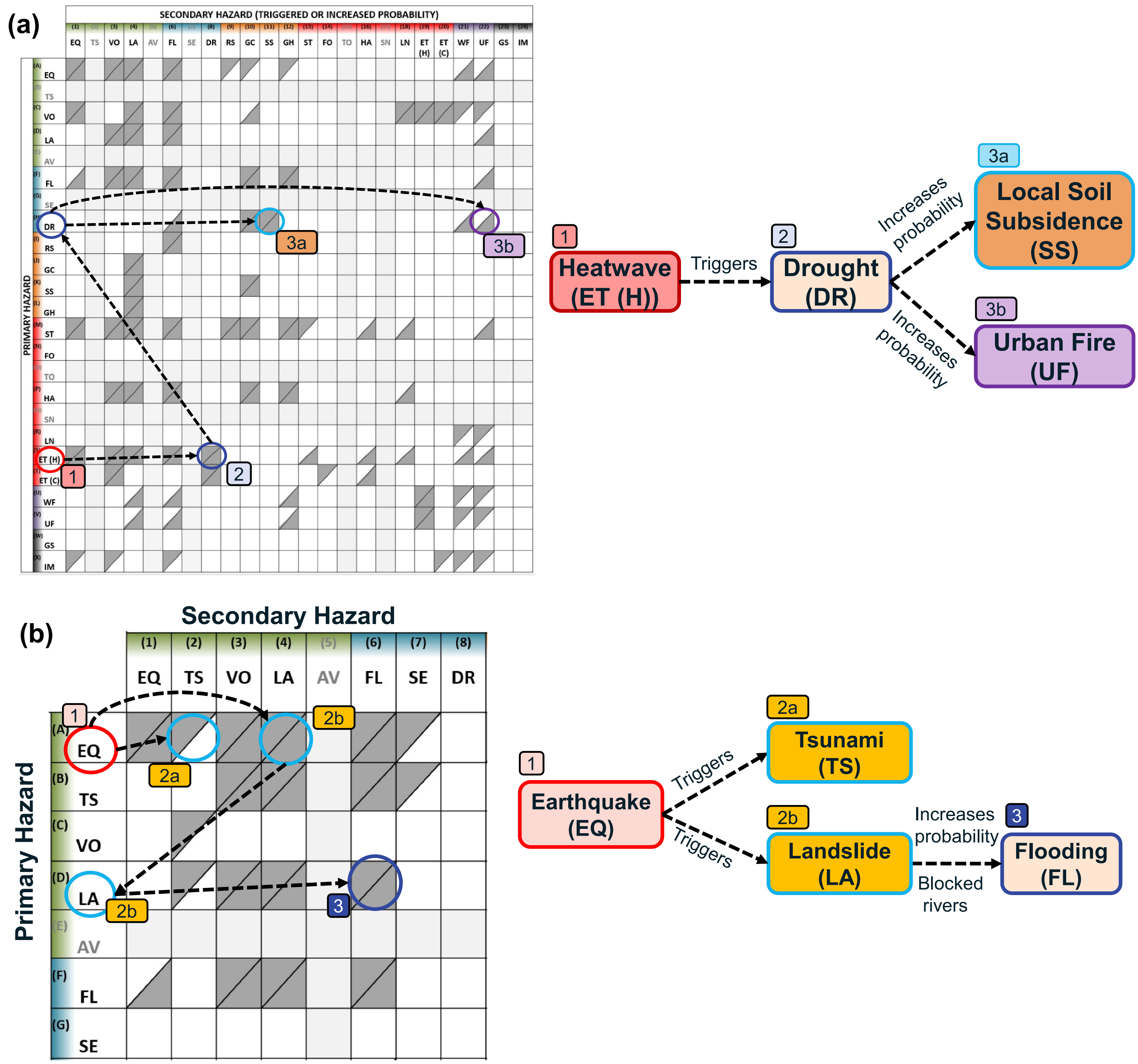

Figure 6. Two example multi-hazard scenarios from the multi-hazard interrelationship matrix in (a) Nairobi and (b) Istanbul. Shown on the left hand side is the matrix version of each cascade, and the right-hand side a cartoon illustration. These examples were used as illustrations of risk scenarios in workshops. The two scenarios given are the following: (a) (Nairobi) a heatwave (ET(H)) triggers a drought (DR), which simultaneously increases the probability of local soil subsidence (SS) and urban fire (UF); (b) (Istanbul) an earthquake (EQ) simultaneously triggers a tsunami (TS) and a landslide (LA). Landslides can further increase the probability of flooding (FL) by blocking a river.

exposure, vulnerability and impact) emerged in the discussions. They considered various interrelationship types, including triggering, increased probability, compound, and cascading interrelationships.

Based on the example scenarios presented in Table 1, Figure 7 shows four multi-hazard scenarios (two from Istanbul and two from Nairobi) created by participants.

In Nairobi (Figure 7a), practitioner stakeholders identified storm-triggered flooding as a significant scenario for both present and future contexts. They also recognized other hazards (Figure 7b), such as landslides and ground collapse, as part of a hazard cascade following storm-triggered flooding. While the focus was on natural hazards, participants emphasized the importance of flood-induced communicable diseases: "*A lot of people say actually*

Table 1
Examples of Multi-Hazard Scenarios Identified by Participants During Workshops and Interviews as Scenarios of Interest for Future Nairobi (N) and Istanbul (I)

Research activity	Nairobi (N) participants, example scenarios	Istanbul (I) participants, example scenarios
Workshops	**N-1: Storm → Lightning → Urban Fire**	**I-1: Heavy rains (storm) + Earthquake → Flood + Landslide + Tsunami + Regional Subsidence + Ground Collapse**
	N-2: Earthquake → Urban Fire	**I-2: Earthquake → Ground Collapse** + building collapse → **Urban Fire**
	N-3: Heavy Rain (**Storm**) → **Flooding → Landslides**	**I-3: Storm → Flood**
	N-4: Heavy Rain (**Storm**) → Flash Floods (**Flooding**) due to poor drainage → Riverine Floods (**Flooding**) → Collapse of buildings	**I-4: Storm → Flood + Hail +** (coincident) **Earthquake**
	N-5: Heavy Rain (**Storm**) → **Flooding** → Electricity blackout, people start using candles/paraffin → **Urban Fire**	**I-5: Earthquake** → infrastructure damage (e.g., dam break) → **Flood**
	N-6: Heavy Rain (**Storm**) → **Flooding** → Short Circuits → **Urban Fire**	**I-6:** Rains (**Storm**) -> dam collapse -> **Flood**
	N-7: Storm -> Flooding + Landslides + Ground Collapse	**I-7: Lightning -> Fire**
	N-8: Drought and no waste management → **Flooding + Urban Fire**	**I-8: Extreme Temperature (Heat)** → rain (**Storm**) → **Flood** → building collapse **+ Landslide + Ground Collapse** or **Heave** + infectious disease
	N-9: Heavy Rain (**Storm**) + **Windstorm → Flooding** and fall of electric poles → **Urban Fire** and electrocution	**I-9: Earthquake → Liquefaction** + ground deformation
	N-10: Extreme Heat → Wildfire	**I-10: Earthquake → Landslide + Tsunami + Urban Fire** + release of hazardous chemicals & contaminants
	N-11: Heavy Rainfall (**Storm**) + **Lightning** -> **Urban Fire**	**I-11: Earthquake → Dam break → Flood → Landslides**
	N-12: Heatwave -> Drought and at same time **Wildfire** followed later by **Flooding -> Ground Collapse**	**I-12: Earthquake -> Multiple Urban Fire events**
	N-13: Flooding → Landslides + Ground Collapse → Landslides resulting in collapsing electricity poles → **Urban Fire**	**I-13: Earthquake + Extreme Cold → Amplified Earthquake Losses**
	N-14: Flooding → Communicable Diseases	**I-14: Heatwave → Drought → Forest Fires**
	N-15: Flooding + Lightning -> Urban Fire	**I-15: Earthquake → Tsunami → Floods and Fires**
Interviews	**N-16: Drought** followed by a **Storm → Flooding**	**I-16: Earthquake → Tsunami → Landslide**
	N-17: Flooding → Landslides	**I-17: Earthquake -> Liquefaction**
	N-18: Flooding → Urban Fire due to improper wiring	**I-18: Earthquake → Landslide**
	N-19: Lightning → Urban Fire	**I-19: Earthquake** → dam damage → **Flood**
	N-20: Flooding -> Water pollution and environmental contamination -> **Diseases**	**I-20: Earthquake → Tsunami** + dam damage **+ Urban Fire → Flood**
	N-21: Storm → Flooding → Landslides	

Note. Bolded text in the table refers to a natural hazard as given in the Figure 2 classification scheme.

the flooding is not the issue because that we can deal with. It's the disease that comes after that…" (Nairobi Interviewee). This issue is linked to inadequate urban drainage and poor solid waste management, particularly in informal settlements.

Of the 21 multi-hazard scenarios identified by Nairobi participants (Table 1), 11 of them include urban fire. While participants identified scenarios of urban fires triggered by lightning (Table 1, Scenarios N-1, 11, 15, 19), most discussions and resulting scenarios focused on the interrelationship of heavy rainfall (e.g., N-5, 6, 9, 11), windstorms (N-9), flooding (N-5, 6, 9, 13), drought (N-8), earthquakes (N-2), and landslides (N-13), and how these result in urban fires (Figures 7a and 7b). Participants identified that interrelationships of these hazards were made more probable through anthropogenic influences, for example, electrical poles with poor electrical wiring, wires sparking fires igniting urban fires in their contact with properties, and sometimes resulting in electrocution of people.

In Istanbul, workshop discussions primarily focused on earthquake-related scenarios, where participants recognized earthquakes as a key hazard with the potential to trigger other hazards post-event. This focus on

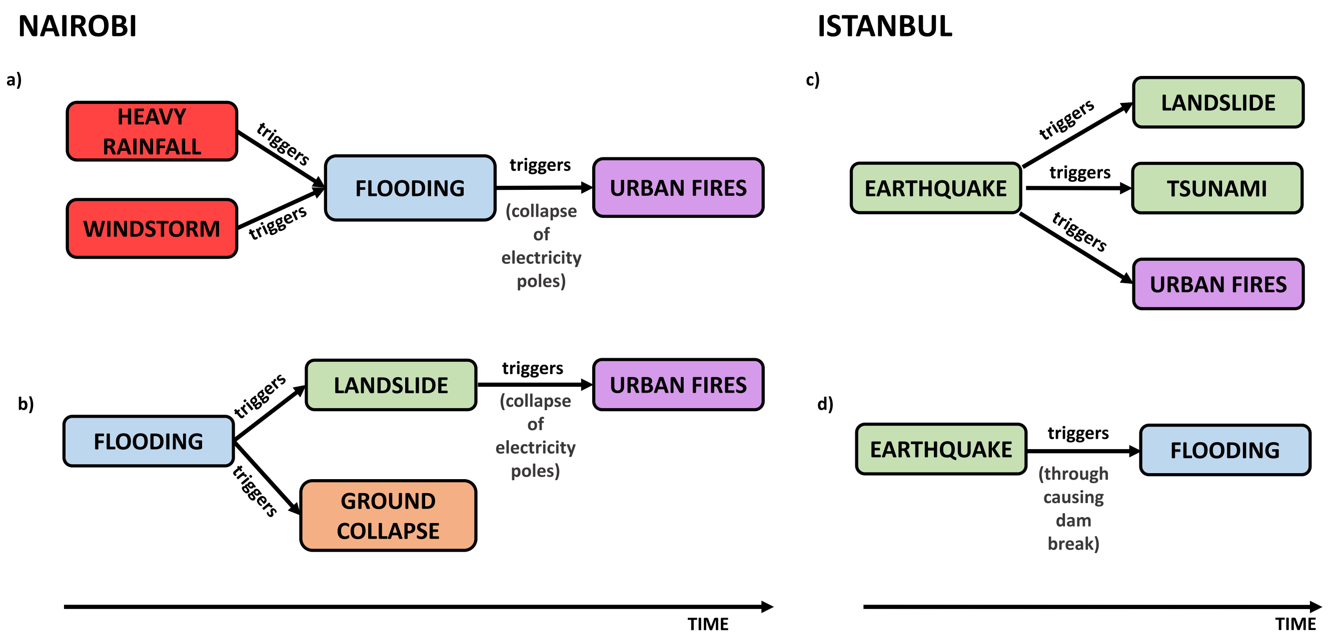

Figure 7. Example of four multi-hazard scenarios produced through disaster risk reduction stakeholder engagement in (a, b) Nairobi and (c, d) Istanbul.

earthquake-related scenarios is evident in 15 of the 20 scenarios in Table 1, which lists various aftermath hazards such as tsunamis, landslides, floods, and urban fires. A notable scenario (Table 1, Scenarios I-5, 11, 19, 20; Figures 7c and 7d) involved an earthquake and subsequent flooding from damaged or collapsed critical infrastructure (e.g., dams). Storm-triggered flooding was also identified as significant, considering Istanbul's projected future growth. As in Nairobi, while emphasizing natural hazards, participants acknowledged the importance of scenarios involving other hazards, such as epidemiological and environmental.

During the workshops and interviews, stakeholders discussed how risk, exposure, and vulnerability dynamically change in multi-hazard scenarios. Examples included:

- In Mathare, an informal settlement within Nairobi, residents move to higher ground post-floods, only to face landslide risks, altering their exposure.
- In the Nairobi workshop, a participant gave another example of dynamic exposure: "*I have seen situations where people move away from their original homes destroyed by fire, resettled in flood-prone zones, and then when the floods come, they get affected.*"
- Dynamic vulnerability in Nairobi was also illustrated by people moving away from fire-affected areas to places lacking social networks and employment opportunities.
- During storms involving strong winds and rains, informal settlements in Nairobi often lose electricity, leading people to use candles, thus increasing their vulnerability to urban fires.
- In Istanbul, exposure (e.g., dams) and impact to the exposure (e.g., the dam rupturing due to earthquakes) were highlighted by several participants.

3.3.2. Benefits of Integrating Multi-Hazards in Disaster Risk Reduction

Stakeholders in both Nairobi and Istanbul indicated that multi-hazards are not adequately integrated into DRR policy and practice. Examples of their application are scarce, limited in the number of hazards considered, and seldom account for interrelationships. In Nairobi, an instance of multi-hazard consideration was shared by an interviewee, who mentioned that floods and urban fires were recently factored into urban planning, such as planning new settlements away from flood zones and using more permanent building materials in informal settlement upgrades.

In Istanbul, multi-hazard integration in policy and practice is more advanced than in Nairobi, but participants pointed out that there is still significant room for improvement. Workshop participants shared examples:

- The Istanbul Risk Reduction Plan identifies 14 key hazards for the city based on their likelihood or impact (AFAD, 2021). However, it does not fully adopt a multi-hazard approach as it treats hazards as isolated events.
- The Istanbul Water and Sewerage Administration has contemplated scenarios where earthquakes damage dams, leading to flash flooding; however, other hazards were not considered.
- "Land suitability" maps have been developed, combining various geohazard data such as liquefaction, flood, and tsunami inundation, and landslide susceptibility. However, these maps do not account for hazard interrelationships.

Overall, participants identified many ways where multi-hazard thinking (including consideration of multi-hazard scenarios) can help build disaster and urban resilience in Nairobi and Istanbul.

In Nairobi, workshop and interview participants highlighted several potential benefits of improved multi-hazard consideration:

- *Increased preparedness and understanding of impact.* Consideration of multi-hazards can help with different preparedness activities; for instance, planning around what might happen and what possible impacts could be, increasing awareness of different stakeholders (e.g., on cascading impacts), identification of vulnerable groups and targeted interventions, planning of early actions and impact-based early warning systems.
- *Enhanced disaster response and recovery*: Better preparation for coordinated responses, including identifying impacted groups and emergency budgets, leading to minimized event impacts, and reduced recovery time.
- *Risk creation prevention*: Actions to prevent new risks, such as improving stormwater drainage and incorporating risk-informed planning in new developments.
- *Capacity and resource needs assessment*: Multi-hazard scenarios help ascertain the capacity and resource planning needs of organizations involved in DRR.
- *Informing urban planning, regeneration, and policy development*: To inform planning processes through risk-informed planning, as well as the review and development of associated policies (e.g., land use policy). Furthermore, multi-hazard scenarios can be used to "stress-test" the existing policies.

In Istanbul, there were similarities in perceived benefits. For instance, as in Nairobi, participants felt that a more detailed consideration of multi-hazards could deepen understanding of impacts and improve disaster response by enhanced planning for a coordinated response. However, further points were raised:

- *Supporting climate change adaptation through DRR*: Climate change-induced increases in frequency and magnitude of some hazard events, particularly meteorological hazards, will require multi-hazard approaches for preparedness and response.
- *Creation of inclusive disaster risk management policies*: Consideration of dynamic risk and socio-economic factors through multi-hazard approaches. Emphasis on how community vulnerabilities and pro-poor approaches could be further included in policies.
- *Improvement of existing plans*: Full consideration of multi-hazards would enhance existing risk reduction initiatives (e.g., risk reduction plans and urban planning documents).

3.3.3. Perceived Challenges and Opportunities for the Use of Multi-Hazard Thinking and Scenarios

As the results presented in the previous section showed, workshop participants and key informant interviewees saw much potential for multi-hazard thinking to improve their current activities; yet, as they pointed out, this is not mainstreamed into practice. Through stakeholder engagement, we identified several existing challenges and opportunities.

In both Nairobi and Istanbul, governance-related challenges were a significant concern. Participants noted issues such as siloed DRR approaches among individuals, departments, and organizations. Current practices were described as short-term and hazard-focused, leading to disjointed implementation due to different agencies handling various hazards. Additionally, there was a noted lack of coordination and communication among actors, with an absence of consideration for trade-offs and synergies in risk management. Further, emerging governance challenges identified by participants were:

- Lack of enforcement of regulations (e.g., building laws, planning policies).
- Lack of implementation instruments (e.g., regulatory or economic instruments) in plans and policies leading to inadequate implementation of planned projects and policies.

- Centralized policymaking, with inadequate inclusion of communities at risk and grassroots organizations.
- Insufficient human (e.g., staff with knowledge on technical aspects of risk) and financial resources, with inadequate transparency over allocation of budgets and financial decision-making.
- Politicians are more interested in short-term and quick fixes rather than multi-hazard issues that often go beyond electoral cycles.

Further challenges identified through workshops and interviews were:

- *Understanding of multi-hazards*: Lack of research on hazard interrelationships coupled with a lack of data on these issues.
- *Response-focused disaster risk management*: The general approach to managing disasters is geared toward responding to events, which hinders the integration of multi-hazards in overall risk management.
- *Focus on imminent risks*: Many communities currently focus on alleviating imminent risks to their well-being and livelihoods; for urban poor communities, this state of chronic emergency prevents people from planning and preparing for longer-term risks or multi-hazards.

Despite challenges, participants in both cities identified opportunities for integrating multi-hazard considerations into policy and practice. In Nairobi, ongoing policy and legislation development (e.g., land use policy) and upgrading informal settlements were seen as chances to include multi-hazard approaches. An increasing awareness and perception of the importance of multi-hazards among policymakers and practitioners was also recognized as a catalyst for change. A Nairobi workshop participant noted the emergence of a community of practice discussing these issues. In Istanbul, workshop participants acknowledged ongoing studies on multi-hazards and a growing political will for their integration into policy and practice.

4. Discussion

In this section, we discuss the five following themes: (Section 4.1) multi-hazard scenarios in context: going beyond natural hazards, including impacts, and influence of anthropogenic activities; (Section 4.2) multi-hazard scenarios: the importance of dynamic risk and risk components; (Section 4.3) mainstreaming multi-hazards in DRR; (Section 4.4) study limitations; (Section 4.5) scalability of the approach developed beyond Nairobi and Istanbul.

4.1. Multi-Hazard Scenarios in Context: Going Beyond Natural Hazards, Including Impacts, and Influence of Anthropogenic Activities

Identifying single hazard types and potential hazard interrelationships in Nairobi and Istanbul underscores the wide array of different natural hazard types (19 in Nairobi and 23 in Istanbul) and their interrelationships (88 identified in Nairobi and 105 in Istanbul) when considering DRR. The number of hazards and interrelationships indicates the necessity of breaking away from single-hazard-focused "siloed" approaches and avoiding an excessive focus on only a few hazard types, as this might lead to an underestimation of the overall risks involved. For instance, the February 2023 earthquakes in Türkiye exemplified this, coinciding with cold weather, which complicated search and rescue operations.

Developing multi-hazard scenarios allowed us to explore how different hazards interrelate in such scenarios. However, our findings, particularly in Nairobi, emphasize the inclusion of hazards beyond natural ones, especially health hazards (i.e., biological hazards). As shown in Table 1, Nairobi practitioner stakeholder participants considered these anthropogenic hazards both in terms of cascading effects after flooding in informal settlements, as well as compound events (e.g., the COVID-19 pandemic and flooding in 2021).

Multi-hazard scenario-building and hazard interrelationships need to consider "non-natural" types of hazards, as this presents the reality of the situation on the ground. The latest hazard classification by the UNDRR and ISC (2021) identifies 308 individual hazard types in the following eight hazard clusters: meteorological and hydrological, extraterrestrial, geo, environmental, chemical, biological, technological, and societal. Multi-hazard analysis, therefore, could benefit from extending the hazard categories used in our work.

Furthermore, our results demonstrate that when constructing multi-hazard scenarios, impacts often constitute an inherent aspect of these scenarios. For instance, Table 1 illustrates that structural damage to electricity poles in Nairobi often serves as a catalyst for urban fires, while in Istanbul, building collapses during earthquakes also lead to urban fires. An example of steps toward expanding the original matrix by Gill and Malamud (2014) was made by Matanó et al. (2022) in Kenya, who incorporated socio-economic impacts (e.g., fatalities and injuries, water shortage, food insecurity) and political disruption (e.g., government elections, changes in government structure).

Our findings also show that anthropogenic activities can significantly influence different components of risk (e.g., hazard frequency and magnitude, exposure, vulnerability) in a multi-hazard scenario. Poor drainage, blockages, and inadequate maintenance heighten flood risk in Nairobi, especially in informal areas. Similarly, unplanned and illegal electricity connections are a common cause of urban fires. Participants' discussions highlighted how anthropogenic activities and natural hazards are interlinked in Nairobi. Examples include urban fires starting from faulty wiring after storm-induced flooding or fires caused by using paraffin lamps and candles during power blackouts. Such influences are particularly prevalent in informal settlements (Owuor & Mwiturubani, 2021), often arising from chronic issues such as poverty and lack of access to essential services.

Beyond these social determinants of risk, the anthropogenic influence on hazards can be understood through a systematic overview of anthropogenic processes (e.g., subsurface mining, vegetation removal, chemical explosions) and their role in triggering and influencing different natural hazards (Gill & Malamud, 2017). For example, a study of global landslides between 2014 and 2016 found that landslide occurrence triggered by human activity has been increasing, and future incidents of deadly landslides are more likely to be due to anthropogenic disturbances rather than climate-related factors (Froude & Petley, 2018).

Anthropogenic influences and processes need to be integrated into multi-hazard scenarios, as these strongly contribute to the very initiation of hazard interrelationships (e.g., urban fire starting after heavy winds interacted with improper wiring, floods happening due to clogged waterways as the result of inadequate waste management).

4.2. Multi-Hazard Scenarios: The Importance of Dynamic Risk and Risk Components

Disaster risk and all its components (e.g., hazard frequency and magnitude, exposure, vulnerability) are inherently dynamic. As presented by Gill et al. (2021), the dynamics of risk can be described through four statements:

- *Statement 1*: Hazards often involve multiple types with interrelationships. Hazards can interconnect through mechanisms such as triggering, increased probability, cascading, and compounding, affecting risk changes.
- *Statement 2*: The hazard landscape is dynamic. Hazard environments change due to factors such as human activities or dynamic hazard-forming environments (Gill & Malamud, 2017; B. Liu et al., 2016).
- *Statement 3*: Changes in exposure and vulnerability impact multi-hazard scenarios. Developments such as construction, vegetation removal, or socio-economic shifts can alter exposure and vulnerability over time.
- *Statement 4*: Multi-hazard scenario progression affects exposure and vulnerability. de Ruiter and van Loon (2022) note differences in vulnerability changes during prolonged disasters (e.g., droughts) and interrelated disasters where an earlier event's impacts alter vulnerability and exposure for subsequent events.

Our findings highlight that constructing multi-hazard scenarios can be an effective tool for capturing and discussing dynamic risk factors, thereby aiding risk management. The scenarios developed in this study align with Statements 1 and 4, illustrating various hazard interactions in the cities and their potential developments. Stakeholders provided examples of how exposure and vulnerability evolve across different scenarios, as detailed in Section 3.3.1. Additionally, Statements 2 and 3, though less emphasized, were considered, particularly regarding how conditions in informal settlements, such as inadequate drainage and waste management or improper wiring, can aggravate risks.

Assessing the dynamics of disaster risks, including their changing components, is a key challenge in natural hazard research (Cui et al., 2021; Šakić Trogrlić et al., 2022). Many risk assessments overlook factors such as changing climate, population growth, urbanization, and environmental shifts (Cremen et al., 2022b). This issue is more complex in multi-hazard risk assessments, which lack standardized approaches (Hochrainer-Stigler et al., 2023; Ward et al., 2022). The method proposed in this paper provides a way to discuss risk dynamics with stakeholders, thereby enhancing awareness and exploring options.

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4.3. Mainstreaming Multi-Hazards in Disaster Risk Reduction

Section 3.3.2 highlighted the benefits of multi-hazard scenarios for stakeholders in Nairobi and Istanbul, suggesting their potential in decision-making regarding dynamic risks and throughout the DRM cycle. Their use throughout the DRM cycle aligns with a recent study by van den Hurk et al. (2023), emphasizing the importance of multi-hazard approaches in five DRR action categories: early warning, emergency response, infrastructure management, long-term planning, and capacity building.

Identified themes for potential benefits primarily enhance preparedness, such as identifying vulnerable populations, early actions, understanding capacity and resource needs, and preparedness for response and recovery. However, the benefits extend beyond preparedness. For example, participants recognized the value of multi-hazard scenarios in (a) preventing the creation of new risks, such as those arising from unplanned development, and (b) reconsidering the decisions of different stakeholders and the impacts of those decisions.

Consideration of multi-hazard scenarios could also support existing national developmental blueprints. For instance, enhancing disaster preparedness is embedded into Kenya's Vision 2030 (Government of the Republic of Kenya, 2007), aimed at transforming the country into an industrializing, middle-income nation with a high quality of life for its citizens by 2030. In line with the Sendai Framework for DRR 2015–2030 (UNDRR, 2015) and the UNDRR (2020) road map, scenarios should adhere to the principle of using a multi-hazard approach. Therefore, the findings presented in this paper could support Kenya's development ambitions and allow disaster preparedness initiatives in Nairobi to be multi-hazard and informed by scenario development.

Our findings reveal that despite recognizing the potential benefits of multi-hazard scenarios, stakeholders see significant challenges in integrating these into practice. Section 3.3.3 outlines challenges related to multi-hazard risk governance, including siloed approaches, centralized policymaking, and human and financial capacity constraints. These challenges are compounded by an overarching focus on response and a reported lack of understanding of multi-hazard risks in terms of both research and data. Similar governance challenges are noted by Scolobig et al. (2014) in Naples and Guadeloupe, and Mignan et al. (2016) in the context of multi-risk reduction, highlighting issues such as inadequate resourcing and communication barriers. These challenges, identified by workshop and interview participants in Nairobi and Istanbul, point to areas in the existing DRR system that require strengthening to integrate multi-hazard thinking effectively in practice.

Our research also highlights technical challenges in studying multi-hazard interrelationships and existing data, which are of a more "technical" nature. The literature reveals various issues, such as knowledge gaps in process understanding, receptor and impact information, and perceived immaturity of multi-hazard assessment science, as noted by Ciurean et al. (2018) in their UK study with natural hazard community stakeholders. Additionally, Kappes et al. (2012) outline challenges including the following: (a) hazard comparability due to different process characteristics, (b) managing relationships between hazard types, (c) conducting a multi-hazard risk analysis, and (d) visualizing a range of natural hazard risks.

Zscheischler et al. (2018) emphasize the importance of including actual and potential multi-hazard events in planning. Our study offers a detailed overview of possible hazard interrelationships, covering both evidenced and physically possible scenarios. Utilizing multi-hazard scenarios could aid risk-informed urban development, a challenging process (Cremen et al., 2023; Galasso et al., 2021) but essential for sustainable, resilient urban futures (Opitz-Stapleton et al., 2019). Based on the process of co-producing scenarios with stakeholders in Istanbul and Nairobi, we argue that they can be a useful tool to aid discussions around multi-hazards, and identify the main challenges and impacts, thus supporting risk-informed planning strategies.

Sharma et al. (2022) argue that to fully realize the potential of multi-hazard scenarios in practice, hazard interrelationships should be modeled and quantified, including an understanding of the spatiotemporal occurrence of multi-hazards (e.g., Claassen et al., 2023). Tilloy et al. (2019) review modeling methods to quantify natural hazard interrelationships between 14 different natural hazard types. They identify 19 different modeling methods, breaking them into three broad approaches: stochastic, empirical, and mechanistic. More recent contributions to quantitatively modeling hazard interrelationships include Yousefi et al. (2020) and Pflug et al. (2024). Modeling (quantitatively or qualitatively as we do via dynamic scenarios in our paper) would be a pre-requisite for operational decision-making, such as allocating shelters for multi-hazard emergency evacuation (Bera et al., 2023), or local land use planning (Barrantes, 2018). For a more in-depth discussion, the reader is referred to Mohammadi et al. (2024) who review current approaches and critical issues in multi-risk recovery planning of urban areas exposed to multi-hazards. Their review includes a section summarizing 27 studies on decision-making models and methods for investment in physical elements to improve recovery in urban areas, categorized into pre-, pre- and post-, and post-disaster actions that have or can be taken.

4.4. Study Limitations

We identify seven main limitations of our study:

(i) *Interrelationship types considered*: Hazard interrelationship matrices in our study, developed from a systematic review and following Gill and Malamud (2014), focused on two types of interrelationships: triggering and increased probability. This approach did not include other interrelationship types such as compound, coincident, consecutive, and independent. Nonetheless, Table 1 shows that stakeholder engagement helped to identify additional types within multi-hazard scenarios, specifically compound and coincident hazards.

(ii) *The reality of stakeholder engagement*: Given the wide range of natural hazards identified, involving all possible stakeholders in workshops and interviews was impractical. Nonetheless, we strived to incorporate views from a diverse group, including academics, non-profits, governmental workers, and policymakers, with varying hazard-specific backgrounds. Stakeholders were selected through ongoing project activities and local partners in the respective cities, ensuring on-the-ground insights.

(iii) *Language barriers in evidence gathering and stakeholder interactions*: Our evidence review was limited to English-language materials, thus excluding many Turkish and Swahili sources. We attempted to mitigate this by exploring diverse sources of blended evidence types, as detailed in Section 2. While Nairobi workshops were conducted in English, those in Türkiye were in Turkish, and simultaneous interpreting services were provided. Detailed workshop notes were translated into English by Türkiye-based research team members.

(iv) *Difficulty accessing evidence of hazard interrelationships*: As noted in Section 2.2, finding evidence for hazard interrelationships was challenging, often due to the lack of explicit discussion in sources. This difficulty partly stemmed from our methodology, which relied on simple Boolean searches rather than a comprehensive systematic review (e.g., using PRISMA protocol) or text mining techniques (de Brito, 2021; Sodoge et al., 2023).

(v) *Predefined hazard types and interrelationship matrices*: Gill et al. (2020) note that stakeholders' perceptions of hazard types and interrelationships might differ from those presented in workshops. The pre-prepared matrices were used to structure discussions, but participants were encouraged to share insights extending beyond these predefined frameworks.

(vi) *Case study limitations in generalization*: Focusing on Nairobi and Istanbul, our research faces challenges in generalizing findings to other contexts. Case studies are often critiqued for their limited generalizability. However, in case study research, generalization pertains more to theoretical expansion ("analytic generalization"), rather than frequency quantification (Yin, 2017). Bazeley (2013) argues that case studies can provide valuable insights into processes and causalities, thereby enhancing theoretical understanding. In our case, this primarily involves insights into the challenges and opportunities of integrating multi-hazards in practice and their potential usefulness.

(vii) *Emphasis on specific multi-hazard scenarios*: Our exemplar scenarios (Figure 7) and corresponding discussion primarily involve urban fires and flooding in Nairobi, and earthquakes and flooding in Istanbul, aligning with the Tomorrow's Cities project's main hazards. Although we identified 19 different hazard types in Nairobi and 23 in Istanbul, the study mainly explored scenarios centered on these specific hazards. Nonetheless, other hazards were also considered during stakeholder engagement through the co-production of multi-hazard scenarios (Table 1), such as storms, drought, heatwaves, lightning, wildfire, tsunamis, landslides, and ground collapse.

4.5. Scalability of the Approach Developed Beyond Nairobi and Istanbul

The systematic and comprehensive methodological approach developed in this paper (outlined in Section 2 and summarized in Figure 1) for examining the breadth of single hazard types and hazard interrelationships in urban areas can be implemented in various geographical contexts. The replicability of the approach is similar to the regional approach of Gill et al. (2020), which was used as a basis for this paper, and to a more recent national-level approach for Sweden by Gustafsson et al. (2023). We show that a systematic review of various sources of evidence (i.e., blended evidence) can lead to a rich understanding of hazard interrelationships in urban areas, which is especially relevant for the urban areas in low and middle-income countries where data is often scarce (Osuteye et al., 2017). Based on the hazard interrelationships identified through systematic search, a step further can be taken toward creating multi-hazard interrelationships scenarios, which can facilitate discussions between different stakeholders working on DRR in urban areas. These scenarios can then be used to ensure effective disaster preparedness and response systems, aid land-use planning, or be used in awareness-raising activities with at-risk communities (Gill et al., 2020).

In addition, our approach emphasizes co-production and involvement with stakeholders in not only the generation of multi-hazard scenarios but also in discussing barriers and opportunities for their integration in practice. This principle can be followed in other urban areas, as co-production is central to urban planning (Frantzeskaki & Kabisch, 2016) and DRR (Filippi et al., 2023). Finally, the challenges for multi-hazard integration in policy and practice identified in Nairobi and Istanbul are similar to those found in other geographical settings, including Naples and Guadeloupe (Scolobig et al., 2014). Consequently, other contexts can learn where improvements are needed, offering a useful contribution to developing localized approaches.

4.6. Methodological Reflections on Stakeholder Engagement Activities

As explained in Section 2, this study was based on mixed methods, including a systematic review of evidence and stakeholder engagement activities in the form of interviews and workshops. From this process, we draw the following lessons which could be useful for future stakeholder engagement activities in the context of multi-hazard research:

- *Introduction of the concept of multi-hazards:* Our stakeholder engagement showed that multi-hazard thinking, especially regarding hazard interrelationships and multi-hazard scenarios, requires a careful explanation of the concept to stakeholders. In this context, hazard interrelationship matrices were identified as a useful visualization tool. Scenarios based on the matrices (examples in Figure 6) were used to introduce the concept to stakeholders through a presentation and a virtual wall (Padlet). Afterward, the stakeholders continued to create their examples, and interestingly, these went beyond just natural hazards and included impacts and anthropogenic influences and processes, which speaks to the value of participatory research with stakeholders in the context of multi-hazards.
- *Selection of stakeholders:* Stakeholders involved in workshops and interviews were selected by the Tomorrow's Cities project teams in Istanbul and Nairobi. All stakeholders had a relationship with at least one team member, with many having working relationships developed through previous engagements. These prior relationships resulted in a conversation space where people felt comfortable sharing their insights, as they understood the mission of Tomorrow's Cities and the direct relevance for DRR and urban planning practice in the cities.
- *Use of multiple facilitation tools:* Throughout the online workshops, we relied on multiple virtual facilitation tools, including Padlet, Google Forms, and PollEverywhere. These virtual tools allowed for gathering inputs from all participants, thus reducing unwanted dynamics during participatory activities (e.g., dominant voices). For example, multi-hazard scenarios were generated through the use of Padlet, where participants noted in the virtual wall all of the multi-hazard scenarios they thought were relevant in the context of their city.
- *Iterative refinement of workshop focus:* Workshops in Nairobi were conducted first, and participants were asked to provide feedback on the workshop structure and content. Based on this, workshops in Istanbul were extended (from 2 to 3 hr), and the approach to discussing the dynamics of risk and risk components was changed. In Nairobi, we asked participants to choose a multi-hazard scenario through which they later discussed the dynamics (i.e., how exposure and vulnerability change throughout the multi-hazard scenario); however, participants found this quite challenging and recommended offering simple, pre-defined scenarios, with some examples of dynamics. This approach was then used in Istanbul.

5. Conclusions

Based on case studies in Istanbul and Nairobi, this paper set out to provide an approach to characterize the full breadth of single natural hazards and their multi-hazard interrelationships in low- to medium-income country urban areas, co-develop multi-hazard scenarios of interest for local DRR stakeholders, and identify possible usefulness, challenges and opportunities for mainstreaming multi-hazard thinking in DRR efforts in Istanbul and Nairobi. We applied a mixed-method approach based on a combination of (a) systematic review processes for finding evidence of single hazard types and hazard interrelationships in each urban area and (b) local DRR stakeholder engagement through workshops and key informant interviews.

Our results show that Nairobi and Istanbul are prone to a breadth of possible natural hazard types (19 in Nairobi and 23 in Istanbul) and many potential interrelationships between the hazards (88 in Nairobi and 105 in Istanbul). Considering multi-hazard interrelationships can be a useful tool in considering and co-producing possible multi-hazard scenarios that can inform future DRM and wider urban planning in the cities. These scenarios also offer an opportunity to engage in discussions on the dynamics of disaster risk and its components, with dynamics an important element to be accounted for in building robust and risk-informed DRM strategies.

Furthermore, we show that considering multi-hazards offers benefits across different aspects of DRR. Nevertheless, despite general acknowledgment of these benefits, mainstreaming multi-hazard thinking into policy and practice remains hindered by several challenges, the main one being various aspects of risk governance and priorities.

The field of multi-hazard research, where hazard interrelationships are also considered, has had increasing attention since 2010, based on an increasing number of relevant publications. Therefore, our findings from Nairobi and Istanbul on multi-hazard interrelationships and their applications in practice offer valuable contributions to the existing knowledge base, not just in terms of multi-hazard characterization but also the realities of its integration in policy and practice.

Through engaging with stakeholders on the ground, our results offer a useful contribution to the discussion of multi-hazards and their translation from academic thinking and global policy directions to resilience-building strategies in the cities. The approach developed and used in this paper can be used for exploring multi-hazard interrelationships in different urban settings and could be particularly useful in the context of urban areas in low- and middle-income countries where data is often scarce.

Data Availability Statement

The 140 kb Excel *Nairobi and Istanbul Multi-Hazard Interrelationships Database* compiled using the methodology described in this paper is available in the online open-access repository Zenodo (https://doi.org/10.5281/zenodo.13220740) with CC-BY 4.0 International rights, cited as Šakić Trogrlić et al. (2024).

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