INTEGRATED DISASTER RISK MANAGEMENT: FROM EARTH SCIENCES TO POLICY MAKING

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INTEGRATED DISASTER RISK MANAGEMENT: FROM EARTH SCIENCES TO POLICY MAKING

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Editorial: Integrated disaster risk management: From earth sciences to policy making

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Editorial on the Research Topic
Integrated disaster risk management: From earth sciences to policy making

Integrated disaster risk management (IDRM) is a complex and fundamental process for disaster risk reduction. Its achievement implies global compound challenges whose response must be implemented locally, but also formulated and pursued on sub-national, national and regional scales. In principle, it is oriented towards preventing new disaster risk, reducing existing disaster risk, managing residual risk and permanently controlling disaster risk drivers (Kirsch-Wood et al., 2022). Thus, IDRM is deeply intertwined with urgent milestones such as the sustainable development goals, the adaptation to climate change, the new urban agenda, the financing of sustainable development, and the humanitarian agenda.

The use of science-evidence policy making is a fundamental and necessary ingredient for the attainment of these critical targets. However, the consequences of the global disaster triggered by COVID-19 unveiled that what was “normal” is the source of vulnerability and exposure (Alcántara-Ayala et al., 2021). Therefore, it remains to be seen whether the existing evidence-policy gap generates sufficient concerns about the need to put transformative thinking into action, and any further policy measures are developed accordingly.

The responsibility of science, particularly of Earth sciences, for the betterment of society has long been recognized (National Research Council, 1993), but recent efforts seek to promote the role of geodynamic understanding for disaster risk reduction and sustainability (Ismail-Zadeh, 2018), priority setting and informed decision-making (Satake et al., 2018). The contributions included in this special Research Topic of articles provide insights on deriving Earth Sciences knowledge to disaster risk reduction, and by and large to policy making.

Bwambale and Kervyn were concerned with integrating indigenous knowledge and science to understand and address disaster risk. Analysing floods in the Rwenzori, western Uganda, where there are discrepancies between research, policy, and action, they recognised the convergence of overlaps in the theorising of the process, the acceptance of the diversity of ontological values and self-criticism among policymakers.

Using the lens of the tourism-disaster-conflict nexus, Neef examined the impacts of the tourism sector on post-disaster response and recovery in Vanuatu, especially as this relates to land relations and rural livelihoods. The findings showed the need to implement disaster risk governance strategies in the tourism sector that address power differences and inequalities, which are often at the core of vulnerabilities and compromised resilience.

In evaluating children's understanding of earthquakes and tsunamis in risk areas of Chile, Cabello indicated the importance of science educators in offering learning opportunities that connect hazards as both social and scientific problems with aspects of understanding their causes and impact.

León et al. used a mixed-method approach combining field-collected data and computerised evacuation and tsunami models to analyse the performance of evacuation drills for four K-12 schools in the cities of Valparaíso and Viña del Mar, Chile. Their results showed that following national evacuation strategies could result in significant loss of life in these schools if rapid evacuation onset times cannot be enacted.

Addressing the direct and indirect effects of earthquakes on Bucharest's road networks, Toma-Danila et al. developed a framework that provides means for real-time integration and time-dependent analysis. This enabled the identification of travel times in emergency situations, the need for seismic lifeline retrofits, traffic management, and increased capacities for critical hospitals or new facilities in specific areas.

By undertaking a retrospective view of the 30 years of continuous operations of the Seismic Early Warning System of Mexico, Suárez recognised the difficulties of alerting earthquakes at close distances. He also highlighted future challenges in terms of exploring better ways to use and communicate warnings, including automatic processes to shut down hazardous facilities.

Dramis et al. focused on the development of object-oriented maps as a tool for landslide risk assessment in highly urbanized areas, whose interoperability in data management allows the analysis of the interaction between landslides and vulnerable assets, such as infrastructure.

An agent-based model to integrate dynamic human behaviours into disaster risk management measures and evaluated its effectiveness in reducing human losses was developed by Wu et al. The model was calibrated to simulate the debris-flow event at Longchi town, China. The results suggested that Early Warning Systems were an effective tool in community-based DRM, while their credibility was essential for their effectiveness.

Ning et al. documented that the delivery of large volumes of sediment by debris flows in a short period of time to rivers frequently initiates a perilous chain reaction in mountain valleys. As this often occurs in Southwest China's Sichuan province, they also provided insights into the role of implementing structural engineering measures in preventing further cascading process in this region.

Payo et al. developed a custom database, FORINSEA1.0, for two study areas in the Southeast Asia region to address the need for the systematic preservation of information required to conduct disaster forensic investigations. The latter aims at recognising and addressing the root causes and drivers of disaster risk and disasters (Oliver-Smith et al., 2016).

Based on Markov chain theory, Mignan et al. presented the prototype of an online platform for the pre-assessment phase of "super-catastrophes" focused on the elaboration of a transition matrix of event interactions from which domino effects crossing natural, technological, and socio-economic systems can be modelled and ranked.

Considering current trends in strategies to characterise, assess and manage risk in historic urban areas, Ferreira and Ramírez Eudave offered a perspective for future lines of research, from empirical calibration models to advanced techniques based on artificial intelligence.

From an epistemic perspective, Raška questioned transdisciplinary education, research, and practices for disaster risk reduction and conveyed the message that fostering understanding and justification of diverse epistemic perspectives would, in turn, allow students and professionals develop axioms that can improve the effectiveness of IDRM.

Based on the notions of apparatus and paradigm associated with vulnerability and resilience introduced by Foucault and Kuhn, respectively, Lièvre et al. envisioned the incorporation of an Apparatus-Paradigm articulation. Their findings indicated that although management practices in Arequipa, Peru appear to be focused on the vulnerability paradigm since the 1990s, after 2015 some operations have emerged as resilient but still fall within the vulnerability paradigm.

In order to enable decision makers to undertake retrofitting projects and improve urban risk planning in the city of Arequipa in Peru, Thouret et al. used and compared several numerical codes to model the potential impacts of tephra fallout and frequent mass flows from El Misti volcano on a vulnerable building stock. The proposed methodology for assessing impacts and losses due to mass flows is useful to develop emergency plans. This, in turn, helps raise awareness among local inhabitants and helps stakeholders formulate adequate disaster management policies in Latin American cities exhibiting similar disaster-prone conditions.

Solheim et al. offered an account of the goals and activities of Klima 2050, a Norwegian centre for research-based innovation, focused on developing innovative solutions for climate change adaptation of buildings and infrastructure. They provided insights

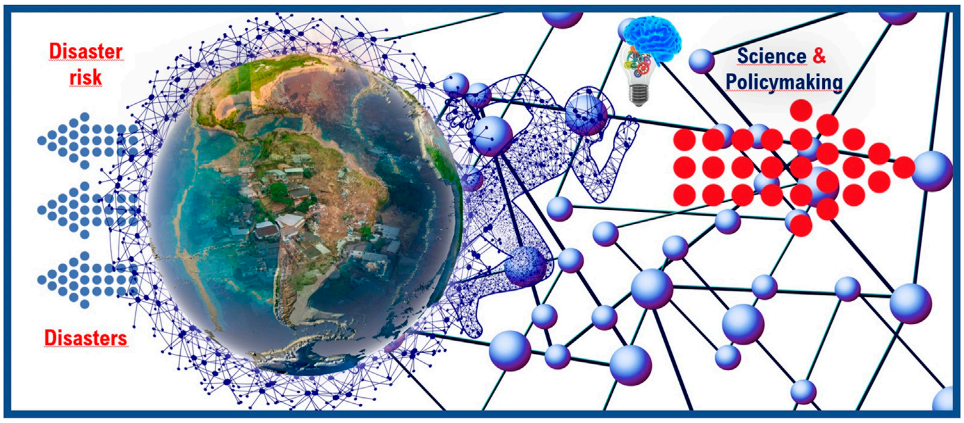

FIGURE 1
A basic interaction scheme between disaster risk and disasters and the need to promote science-based policy-making.

from pilot projects aimed at managing landslide risk, which were carried out based on intersectoral and interdisciplinary collaboration.

The geosciences are beginning to reflect more clearly their interest in the policy making arena. Nonetheless, moving from Earth sciences to policy making is an extremely sensitive endeavour in which knowledge is unbalanced with strategic goals and trade-offs. Holistic, inter and transdisciplinary perspectives are required to understand the interactions and interdependencies among hazards, vulnerability, and exposure to manage the complex dimensions and the political and diplomatic avenues of disaster risk reduction.

Certainly, disaster risk management requires not only the comprehension of the social dimensions and physical dynamics of the planet. It calls for a global understanding and action that advances integrated transdisciplinary science and anticipates the vitalness of a bonding interface between science and policy making, in which co-production of knowledge is the core nature of this key issue (Figure 1).

Global understanding implies global thinking and local action, thus bridging the gap in awareness between local initiatives and strategies and global effects, in which socio-cultural background is highly relevant (Werlen et al., 2016). Likewise, it also necessitates a way of recognising that international policies and models of development, biased in favour of particular sectors of society, influence political frameworks, institutions, policies and the daily course of consequences on laypersons at local scale. This blending of multidirectional and multiscale processes actually mirrors the systemic nature of disaster risk.

The social construction of systemic risk recognises that economic globalization has resulted in a greater complexity, interdependence, non-linearity, feedback loops, and uncertainty of the system (Maskrey et al., 2021). Obviously, this has a considerable impact on IDRM. It therefore becomes paramount and urgent to encouraging a new paradigm for the governance of systemic risk at local and national levels to re-evaluate the trade-off between privatising gains and socialising risks in favour of sustainability and resilience (Maskrey et al., 2022).

Consequently, and in the context of global environmental change, it is very likely that for the foreseeable future, most efforts of applied Earth sciences will need to be directed at answering and addressing issues of governance of the Earth system.

Author contributions

All authors listed have contributed equally and made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The Contentious Role of Tourism in Disaster Response and Recovery in Vanuatu

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Tourism is a key contributor to the economy of the Pacific Island country Vanuatu. Yet many Ni-Vanuatu have seen their access to natural resources lost or reduced as a consequence of foreign investment in the tourism industry and associated land leases, while few community members found secure employment in the tourism sector to compensate for those losses. The tension between externally driven tourism development and local resource access has been exacerbated in the aftermath of 2015 Tropical Cyclone Pam which caused extensive damage both to the tourism industry and local communities. Employing a tourism-disaster-conflict nexus lens and drawing on semi-structured interviews with hotel managers, research conversations with hotel staff and community members, and focus group discussions with community leaders, this study examines how the tourism sector has impacted post-disaster response and recovery, particularly in terms of land relations and rural livelihoods. Findings suggest that tourism can be a double-edged sword for disaster-prone communities. While resorts play an important role as first responders, their contributions to post-disaster recovery processes remain ambiguous and marred by tensions between expatriate investors and indigenous Ni-Vanuatu people. These findings also hold lessons for the tourism crisis triggered by the COVID-19 pandemic in the South Pacific and elsewhere.

Keywords: disaster risk management, post-disaster recovery, land rights, tourism-disaster-conflict nexus, COVID-19, South Pacific

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INTRODUCTION

Tourism crises have often been precipitated by major disaster events. Small island developing states in the South Pacific have been particularly susceptible to tropical cyclones, floods and tsunamis that have had a deep impact on the tourism industry on which these countries' economies depend strongly (e.g., Klint et al., 2012; Loehr, 2020). Yet, surprisingly, there has been very little research scrutinising the role of the tourism sector in the immediate disaster relief response and long-term rehabilitation efforts.

The objective of this paper is to contribute to a better understanding of the role of the tourism industry in post-disaster response and recovery processes, drawing on the example of the 2015 Cyclone Pam in Vanuatu. More specifically, the aim is to determine whether the tourism sector can be a positive force in helping local communities to restore their livelihoods. To this end, it is important to understand 1) how tourism businesses have been affected by Cyclone Pam, 2) how they have responded to and recovered from the disaster, and 3) how their response and recovery strategies have had an impact on their staff and local communities. Particular emphasis is placed on land relations and the rehabilitation of rural livelihoods.

Thereby, the article aims to generate insights that will help inform future governance of disaster response and recovery – including from the COVID-19 pandemic – in touristic areas of Vanuatu and the wider Pacific region.

CONTEXT

The Importance of Vanuatu's Tourism Sector

Vanuatu is an archipelago of more than 80 islands located in the Southwest Pacific (De Burlo, 1989). Its population of over 300,000 inhabitants is divided into more than 100 distinct linguistic and cultural groups. During colonial times, Vanuatu was known as the New Hebrides and subject to a rather unique Anglo-French colonial rule established in 1906 (Farran, 2010). Since gaining independence, Vanuatu's economy has seen relatively steady growth rates, primarily due to a substantial rise in revenues from tourism. Tourism is a key contributor to the country's Gross Domestic Product (GDP), the major foreign exchange earner, and an important employment provider, particularly in the main island of Efate and – to a lesser extent – in the islands Espiritu Santo and Tanna (Loehr, 2020). It is estimated that over 8,000 full time equivalents (FTEs) were employed in the Vanuatu tourism sector prior to 2015 Cyclone Pam (Government of Vanuatu, 2015). Visitor arrivals peaked in 2014, with Australia being the most important source market (about 60%), followed by New Zealand (13%) and New Caledonia (12%), according to data from the Vanuatu National Statistical Office (Government of Vanuatu, 2015).

The tourism sector in Vanuatu is characterized by a "dualistic" structure, whereby prior to Cyclone Pam in March 2015 about one third of the foreign visitors arrived by air and stayed in hotels, resorts and guesthouses for an average of 8–9 days, while two thirds of visitors arrived by cruise ship and stayed only for 1 day without the need for accommodation in the country. Cruise tourists are primarily targeted by local tour and cultural show operators, who are mostly indigenous Ni-Vanuatu whose small businesses are protected by the so-called "Reserved Investments" clause under the Foreign Investment Promotion Act.

Tourists arriving by air have a choice among a wide range of accommodation, from budget lodges and motels to luxury boutique resorts. On the major islands, the hotel business – which is much more capital-intensive than tour operations – is dominated by foreigners, who benefit from favourable investment conditions, such as tax exemptions and relatively low lease rates for beachfront properties (MTICNB, 2013). On the main island of Efate, considered the accommodation gateway to Vanuatu, three large hotel operators accounted for about 30% of the available room stock in 2014 (Government of Vanuatu, 2015).

A Brief History of Land Rights Systems in Vanuatu

In precolonial times, land on the various islands in what is today's Vanuatu was acquired simply by occupation and establishment of the first meeting house (*nasara*) (Farran, 2010). Ownership was marked by physical evidence, such as graves, boundaries or planted trees, and through oral evidence (Farran, 2008; McDonnell, 2015). Intergenerational transfer of land was matrilineal in some communities and patrilineal in others (Farran, 2008). Nagarajan and Parashar (2013) contend that the rights of women to use land and be involved in decisions affecting land were recognized under customary law. As in many other South Pacific nations, the links between cultural identity, tradition (*kastom*) and place (*ples*) are foundational for indigenous (Ni-Vanuatu) people (Wittersheim, 2011; McDonnell, 2015).

Throughout much of the 20th century, the indigenous Ni-Vanuatu people were dispossessed of a great share of their customary land by British and French settlers and missionaries (De Burlo, 1989; Farran and Corrin, 2017). Under joint British and French colonial rule indigenous land on the larger islands was allocated to settler plantations, churches and public/administrative purposes. According to Farran (2010), about two thirds of the land in the then New Hebrides were in the hand of foreigners at some point. The two colonial powers introduced the previously unknown concepts of freehold and leasehold and competing sets of laws and legal institutions. Independence from the so-called "condominium government" was only achieved in 1980, after demands for restitution of land alienated by the colonial powers could no longer be suppressed (Farran, 2010).

The 1980 Constitution restored indigenous land ownership across the newly independent country and provided that the rules of custom should form the basis for ownership, control and use of the land (Farran and Corrin, 2017). Yet it was not always easy to identify the legitimate custom owners, and leadership claims were often disputed, and the number of counter-claimants was high, particularly in areas that had been most impacted by colonial settlement (Farran and Corrin, 2017). Chiefly leaders often play a triple role of holding trusteeship over customary land, being figures of authority and acting as adjudicators of disputes (Farran, 2008).

In the early years after independence land leasing activity in Vanuatu was rather modest, confined primarily to agricultural leases of 30 or 40 years. Yet with the advent of tourism and the associated diversification of the economy, non-agricultural leases with a longer duration (up to 75 years) were introduced (Wittersheim, 2011). In 2013, the Vanuatu government introduced a new piece of legislation – the Custom Land Management Act – which was aimed at further strengthening customary land tenure and making it more difficult to alienate land through leases and sub-leases to foreign investors (Farran and Corrin, 2017). However, the implementation of the Act has been constrained by a phase of political instability and the nation-wide disaster caused by Tropical Cyclone Pam in 2015.

Hazards, Vulnerability and Tourism: Tropical Cyclone Pam in March 2015

The tourism sector in Vanuatu is highly susceptible to climate-related disasters, such as cyclones or floods (Loehr, 2020), but also to other natural hazards, such as earthquakes, tsunamis and

FIGURE 1 | Only the foundations remain from this beachfront resort on Efate Island after Cyclone Pam struck the area. Source: Author's own.

volcanic eruptions. Cyclone activity occurs mainly during the months January to March. During this period, tourist arrivals in Vanuatu are the lowest. Between 12 and 14 March 2015, Vanuatu was struck by Tropical Cyclone Pam, an extremely destructive Category five cyclone with wind speeds of about 250 km/h. The cyclone damaged or destroyed an estimated 17,000 buildings, displaced around 65,000 people and affected the livelihoods of at least 80% of the rural population by destroying crops and livestock on a massive scale (Government of Vanuatu, 2015). The damage was most severe on the larger islands of Tanna, Erromango and Efate. The relatively low death toll of eleven people was attributed to indigenous knowledge and the availability of emergency preparation plans in many communities as well as essential information being transmitted across the island *via* social media, the radio and millions of SMS messages (World Bank, 2015; Saverimuttu and Varua, 2016). The long-term damage to the country's economy was estimated to be approximately USD 500 million, equivalent to nearly two thirds of Vanuatu's annual GDP (Saverimuttu and Varua, 2016; Ballard et al., 2020).

According to the Government of Vanuatu's post-disaster needs assessment report, the total damage to the tourism subsector caused by Cyclone Pam was around USD 51.7 million and total losses over the 6 months following the disaster event were estimated at about USD 31.5 million (Government of Vanuatu, 2015). All damages and losses were incurred by private businesses. Two of the three largest operators – which account for 30% of the room stock on Efate Island – had to be closed for several months (Government of Vanuatu, 2015). Many of the small- and medium-sized businesses in the tourism and hospitality sector suffered near-complete damage to their premises (see **Figures 1**, **2**).

Hence, the massive cyclone exposed vulnerabilities of various groups – including the corporate tourism and hospitality sector, the predominantly Ni-Vanuatu employees and local communities – which are linked through complex socio-economic relations and power dynamics. Wisner et al. (2004) contend that the root causes of vulnerability are primarily a result of social relations and structures of domination. Their conceptualization of disaster risk and vulnerability "focuses on the way unsafe conditions arise in relation to the economic and political processes that allocate assets, income and other resources in a society" (Wisner et al., 2004: 92). As this study will show, the proliferation of land leases for tourism has led to uneven power relations between expatriate leaseholders and Indigenous Ni-Vanuatu and compromised access to natural resources for local communities, leaving the latter in a state of heightened vulnerability in the wake of Cyclone Pam.

LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK: THE TOURISM-DISASTER-CONFLICT NEXUS

This study is conceptually grounded in the tourism-disaster-conflict nexus as identified by Neef and Grayman (2018) and depicted in **Figure 3**. In the following sub-sections, the main linkages within the nexus are described with examples from the literature and underpinned by three theoretical concepts.

Linkages Between Tourism and Disaster

The tourism sector in the Global South has been particularly susceptible to disruptive disaster events, as many tourist destinations are located in coastal areas that are at risk from

FIGURE 2 | Cyclone Pam destroyed the terrace of this beachside restaurant on Efate Island. Source: Author's own.

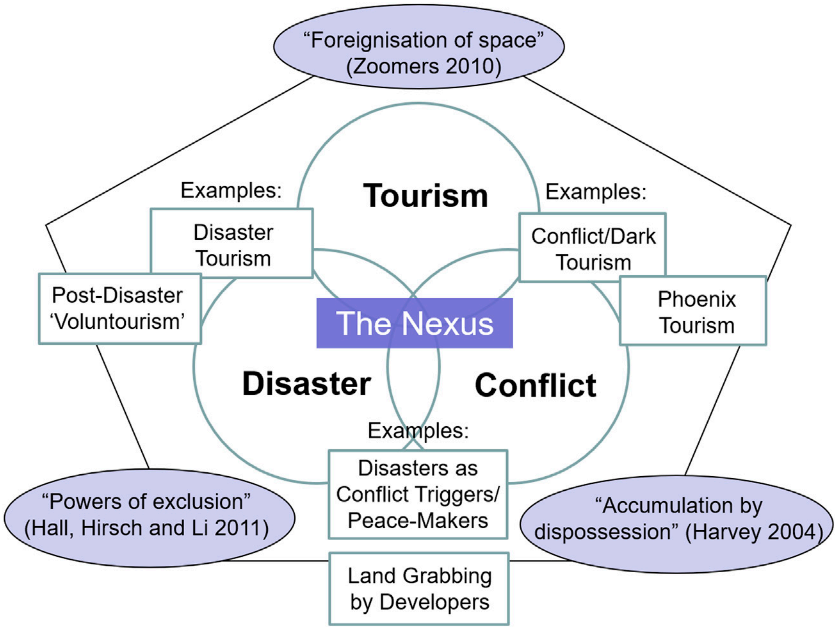

FIGURE 3 | The tourism-disaster-conflict nexus and underlying concepts and theoretical frameworks. Source: Author's own.

tsunamis, hurricanes, cyclones and sea surges. The linkages between tourism and disaster that have received scholarly attention include disaster preparedness and disaster risk reduction strategies in the tourism sector (e.g., Ritchie, 2008; Becken et al., 2014; Calgaro et al., 2014; Hall et al., 2019), tourism as a trigger or amplifier of disasters (e.g., Hall, 2001; Loperena, 2017), the impacts of disasters on the tourism industry (e.g., Calgaro and Lloyd, 2008; Seraphin, 2018), and tourism as a driver of disaster recovery (e.g., Mair et al., 2016; Carrizosa and Neef, 2018). The latter is relevant to this study as the tourism industry has often been assigned a crucial role in reconstruction and recovery efforts following a major disaster. Referring to earthquake-stricken Nepal and cyclone-ravaged Vanuatu, the British newspaper *The Guardian* (Marshall, 2015) coined the catchphrase "your holiday can help," whereby prospective tourists are nudged to support post-disaster rehabilitation simply through visiting disaster-affected areas. Yet such forms of disaster tourism may have unintended consequences, since less touristic areas that have been severely affected by the disaster may receive less humanitarian relief support. In southern Thailand, for example, post-disaster recovery efforts following the 2004 Indian Ocean Tsunami were primarily targeted at prime tourist destinations, while rehabilitation efforts in other devastated areas were neglected or delayed (Calgaro and Lloyd, 2008; Neef et al., 2015). An important and emerging subfield of critical tourism studies has focused on post-disaster volunteer-tourism, or "voluntourism," whereby visitors from the Global North volunteer for social or environmental causes while on holiday. Following 1996 Hurricane Mitch that devastated parts of Honduras, US American tourists were lured with discounted airfares into vacationing on affected tropical beaches, with debris removal, tree planting and restoration of turtle nesting sites all part of the holiday package (Mowforth and Munt, 2016).

Linkages Between Tourism and Conflict

Linkages between tourism and conflict include the idea that tourism can be a force for peace and stability (e.g., Farmaki, 2017), the notion of dark tourism or thanatourism (e.g., Light, 2017), the concept of phoenix tourism in post-conflict destination rebranding (e.g., Causevic and Lynch, 2011), and tourism-induced conflicts over land and resources (e.g., Devine, 2017). The latter linkage is particularly relevant for the context of this study, given the ongoing contestations over land ownership and leases in Vanuatu and other countries in the South Pacific. As Neef and Grayman (2018) maintain, small islands are particularly prone to conflicts over land and other natural resources triggered by tourism development, as they face challenges of resource scarcity, particularly with regard to freshwater, and have limited carrying capacity (cf. Gössling, 2003). Land tenure legislation tends to favour local elites and wealthy foreigners who can easily claim the foreshore for "public" purpose, such as tourism, while often disregarding customary rights of communities that depend on coastal land and other natural resources for their subsistence (Knudsen, 2012; Benge and Neef, 2018).

Linkages Between Disaster and Conflict

The linkages between disaster and conflict include disasters as triggers or intensifiers of civil conflict and ethnic tensions (e.g., Weir and Virani, 2011; Eastin, 2016), disaster diplomacy and conflict resolution (e.g., Le Billon and Waizenegger, 2007), and the notion of disaster capitalism (Klein, 2007) which describes the predatory behaviour of private and public actors that consider disasters as opportunities to capitalize on temporary or permanent vulnerabilities among affected communities. Several studies have shown how disasters, such as the 2004 Indian Ocean Tsunami and 2013 super-typhoon Haiyan, have triggered land conflicts as investors took advantage of the absence of local landowners due to their temporary relocation to disaster shelters or their permanent resettlement from coastal areas following arbitrary setback policies for coastal communities imposed by the government (Attavanich et al., 2015; Uson, 2017). When such opportunistic and predatory investors are involved in the tourism sector, then the nexus of tourism, disaster and conflict is complete in all its interlinkages. Recent studies that have examined the intersection of tourism, disaster and conflict include Cohen's (2011) research on post-tsunami land grabs in Thailand, Sri Lanka and India, Pyles et al. (2017) study on post-earthquake disaster capitalism in Haiti and Loperena's (2017) analysis of tourism's extractivist expansion in the case of post-disaster Honduras. What has been lacking in these studies was a comprehensive theoretical conceptualization.

MATERIALS AND METHODS

The research was conducted between December 2016 and June 2017 on the country's major island Efate, where most of the tourist infrastructure is located. Around 97% of tourists traveling to Vanuatu stay on Efate (IFC, 2015). It is also the island that sustained most damage from Cyclone Pam. The study focused on the tourism sector in the capital Port Vila, where the concentration of accommodation is highest, as well as on the southern and northwestern part of the island.

The hotels and tour operations were purposively selected to cover a wide range from budget accommodations to luxury boutique resorts and obtain a broad geographic coverage of the major tourist hotspots on the island (see **Figure 4**). The main emphasis of the study is placed on the accommodation sector, includes the three largest room providers on Efate Island and covers more than two thirds of the island's total room capacity. **Table 1** shows a breakdown of the surveyed hotels and tour operations. The business ownership structure appears typical for the tourism sector in Vanuatu. Tour operations are predominantly locally owned, and some of the budget accommodations are also owned by locals (mostly naturalized citizens rather than indigenous Ni-Vanuatu), while the entire range from 3-star hotels to high-end luxury boutique resorts is under the ownership of international hotel chains and affluent business people from Australia, New Zealand and other Global North countries.

The major methods employed in this research were semi-structured interviews with hotel staff and tour operators in management positions, research conversations with non-managerial staff in the tourism sector and community members, and focus group discussions with community leaders. In total, 20 semi-structured interviews, 19 research conversations, and three focus group discussions were conducted by the author and a Ni-Vanuatu research assistant in the capital Port Vila, the southern coast and the northwestern part of Efate, covering all major tourist hotspots of the island. The interviewees comprised three male and three female expatriate hotel managers as well as six male and eight female Ni-Vanuatu in managerial positions. Research conversations followed Pacific research principles of *talanoa* and *stori* which are based on casual talk and sharing of stories rather than formal questions

FIGURE 4 | Map of Efate Island with locations of hotels and tour operations (purple triangles) and communities (blue circles) selected for the study. Source: Adapted from https://commons.wikimedia.org/wiki/File:Map_of_Efate_Island_EN.png

TABLE 1 | Tourist businesses selected for the study, number of interviews and research conversations, and business ownership structure. Source: Author's own.

Type of business	Tour operators	Budget/2-Star hotels	3-Star hotels	4-Star hotels	5-Star luxury resorts
No. of businesses	4	4	6	8	4
Business ownership	all 4 locally owned	2 foreign, 2 local	all 6 foreign	all 8 foreign	all 4 foreign-owned
No. of semi-structured interviews (managers)	1	3	5	7	4
No. of research conversations (staff)	3	1	3	6	5

and answers (Vaioleti, 2006). Such informal conversations were conducted with nine male and nine female non-managerial staff and one male community chief; all of them were Ni-Vanuatu citizens. The three community focus groups were attended by a total of nine men and ten women and conducted in a similarly informal setting and conversation style. All interviews were held in English, research conversations were conducted either in English or Bislama, and the focus group discussions were entirely held in Bislama.

In addition to primary data collection, we also gathered secondary data from government reports, official tourism development plans, the Vanuatu National Statistical Office and international development reports. This secondary information mostly served the purpose of triangulating the findings from the qualitative study.

Analysis of the primary data was done through a close reading of the written notes from the interviews, research conversations and focus groups, followed by thematic, semi-inductive coding.

Based on initial coding, higher order categories and themes, such as "land relations," "short-term disaster relief," and "long-term recovery" were developed. Emphasis was placed on a thick description of categories and themes, with the aim of providing sufficient depth, breadth and context.

RESULTS

Land Acquisition and Resource Enclosure by Vanuatu's Tourism Sector

The accommodation sector on Efate Island is disproportionately controlled by foreigners who lease waterfront blocks from customary landowners at relatively cheap annual rates. The high demand for beachfront accommodation has led to a proliferation of land speculation among foreign investors. Land conflicts are increasingly common, particularly in the rural areas of Efate, where customary land ownership is often ambiguous.

> "Many local people have sold [leased out] their land without thinking of the long-term consequences. The landowner is usually the main chief in the village and the benefit is meant to be spread evenly, but often that is not the case." (General manager of luxury resort in northern Efate).

> "The land ownership rights over the area where the resorts are located have been transferred to two families. They get most of the benefits from the resorts, the Council of Chiefs also receives some money, but the real customary owners do not receive anything." (Participant in focus group discussion in rural community in southern Efate).

Hierarchical structures and differential access to land are predominant in the communities, and benefits from the proliferation of land leases benefit only a few. Land leases are overwhelmingly the providence of the chiefs; in Northern Efate, for instance, 80 per cent of the 56 leases – mostly acquired by local expatriate investors – that have been signed off by individuals list a local chief as the lessor (McDonnell, 2015). Hence, only a small minority of the local population can actually take advantage of the booming lease market, while many community members feel the negative impacts of the continuing alienation of customary land in the form of leases to foreign investors (Wittersheim, 2011). The situation is particularly dire for women: none of the individual leases in Northern Efate list a woman as the lessor, while all but one communally signed lease contracts list only men (McDonnell, 2015).

It is estimated that over 90% of coastal land on Efate Island has been alienated by foreigners, in most cases for the maximum lease period of 75 years (Trau, 2012). The country-wide lease register makes it easy for foreign investors to use their lease contracts as collateral when taking out a bank loan. Unlike in Fiji, a national register for customary land ownership does not exist in Vanuatu. Hence, many Ni-Vanuatu landowners face problems borrowing financial capital off their customary land, which makes it difficult for them to start their own tourism business (MTICNB, 2013).

> "There are two types of processes to get land here in Vanuatu: either you negotiate directly with the customary landowners or you lease land that has already been developed by someone else. In any case, you have to check the titles carefully with the Lands Department. The leases here are pretty cheap, for a 4,000 m^2 plot you pay around AUD 1,000 per year." (General Manager of luxury boutique resort in southern Efate).

> "Land sales are such a huge business [. . .]. My Australian stepfather bought a plot of land for 3 million Vatu, and we just cleared the land and then he resold it for 23 million Vatu." (Caretaker of 4-star apartment hotel in southern Efate).

While the majority of the interviewed accommodation businesses held 75-years leases from customary landowners, a few of them had leased state-owned land (**Figure 5**). All tour operators managed their business on their own land, and some of the smaller accommodation providers also held ownership rights to their land, mainly stemming from pre-independence times, when land sales to foreigners were still possible.

Many resorts are fenced off, and access to beaches – and sometimes entire islands – are exclusively reserved for hotel guests, with security guards making sure that no trespassing occurs. The enclosure of beachfront properties often leads to reduced access of local people to the sea. Such "spaces of exception and exclusion" affect women's livelihoods, as they engage mostly in fishing from the shore and on the reefs, while fishing in the open sea is dominated by men (Government of Vanuatu, 2015; Eriksson et al., 2017). By contrast, some of the local men are still able to negotiate access to the beach as they often know the hotel guards who hail from their own community.

> "Despite the resorts, we can still get access to the beach and the sea. The security guards are from our community, so we can arrange it with them." (Male respondent during focus group discussion in local community).

Eriksson et al. (2017) have highlighted the importance of fisheries and customary fishery management for disaster recovery among coastal Ni-Vanuatu people. Hence, discrimination of women regarding access to the foreshore has a direct and adverse impact on their potential to contribute to the economic recovery of their families.

Hotel managers portrayed their business operations as beneficial for local communities, lifting people out of poverty. In the interviews, they mentioned staff employment, lease fees, food supply from farmers and fishers, educational support for students, and donations of replaced hotel items as major benefits. These narratives are used as *legitimation* for land appropriation

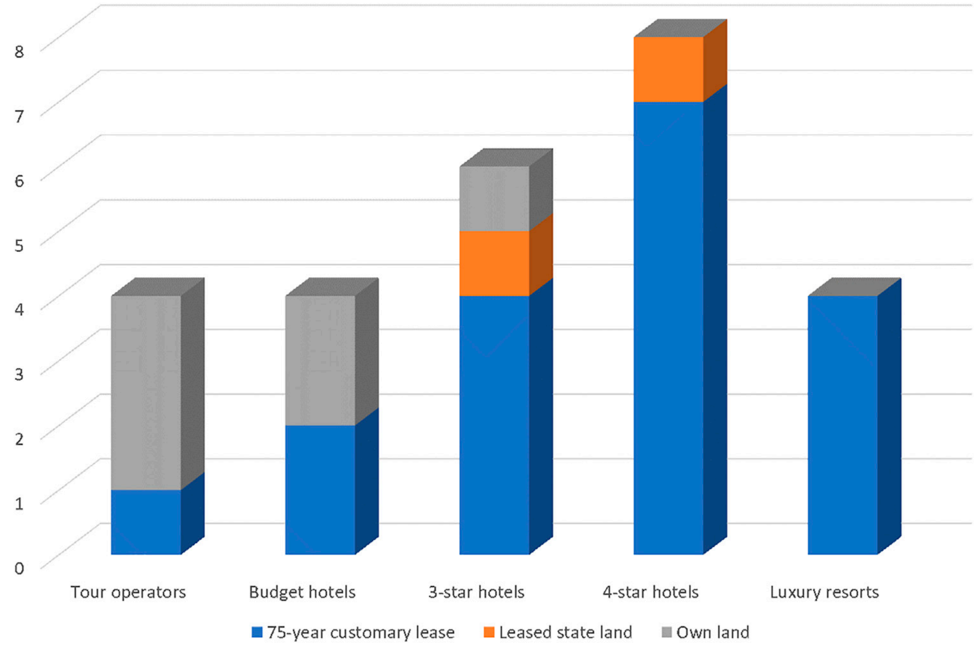

FIGURE 5 | Land tenure status of the surveyed tourism businesses. Source: Author's own.

through leases, which is one of the four exclusionary powers as identified by Hall et al. (2011).

> "Local people benefit a lot from tourism, it is the No. 1 employer, and the unemployment rate here in Vanuatu is as high as 50–60%. Many locals here come from the other islands to seek employment in the tourism sector and then send money to their families back on the islands." (Manager of small 3-star resort in Port Vila).
>
> "[The landowners who leased their property to our hotel] always seem to be happy when they pick up their monthly check and spend some money on eating in our restaurant." (General Manager of 4-star beach resort in Port Vila).

This positive view is not shared by all community members. In two of the three focus groups at community level and in a research conversation with a local island tour operator, participants painted a relatively bleak picture of the impact of tourism on their communities and complained about insufficient support from tourist resorts, the lack of transparency on lease agreements that were concluded several decades ago, and hotels taking a major share of the profit from local village tours. There was also a sentiment that the benefits from the leases are not spread evenly among the villagers.

> "There has been no improvement in our community since the time when the tourism business started in the area. People in the community continue to suffer from poverty." (Brother of the village chief and officer at the Department of Fisheries during focus group discussion).
>
> "In our village, there is a big gap between rich and poor, you can see it when you look at the differences between the houses. The rich ones are those who have sold off their land to the foreigners." (Community-based island tour operator).

In another community, people expressed more satisfaction with the benefits they got from resorts established on their leased properties, referring to improved water supply and employment opportunities provided by the resorts. Some of the resorts have lease agreements that include clauses stipulating that the land-owning community should be given priority in hotel staff recruitments, but the majority does not have such obligations.

> "We hire staff from many different places, whoever is qualified. But in rural areas, the hotel staff is mostly from neighboring villages and its mostly casual work." (Manager at 3-star resort in Port Vila).
>
> "Most of the resort employees come from Port Vila, only a handful are from our community. People are employed through their social networks." (Participant during focus group discussion in a rural community).
>
> "We have no contractual obligations to hire anyone from the landowning community, so we hire only the most skilled people. The landowner used to work as head of security, but this didn't work out and we stopped employing him." (Manager of 4-star beach resort in Port Vila).

In sum, land acquisitions through leases are a form of "accumulation by dispossession" (Harvey, 2004), as the long-term leases remove de-facto ownership to coastal land from the affected communities for at least three generations, while providing limited and precarious benefits to the land-owning communities. The exclusionary powers of regulation, legitimation and the market (Hall et al., 2011) enclose customary land and compromise rural people's livelihood opportunities.

Post-Disaster Relief Support to Local Communities by the Tourism Industry: Effective and Legitimate First Responders?

Our interviews and focus groups with representatives of communities in rural areas – adjacent to tourist resorts – showed that villagers demonstrated a high level of resilience during Cyclone Pam and in the aftermath of the disaster. Village committees helped to bring villagers to safety during the cyclone, and community members organized themselves to rebuild those houses that had been destroyed. However, some respondents also mentioned the challenges of rebuilding houses, while restoring their agriculture at the same time.

> "It was hard for us to find food immediately after the cyclone. We worried about rebuilding our houses and at the same time to find food." (Church assistant during focus group in community).

Many cases were reported in our survey where tourist resorts provided direct help to the communities, particularly to those whose land they were leasing. Initial responses were mostly in the form of food and water supplies, but also included tools, tarpaulins and building materials. Some hotel managers also set up emergency funds to provide more long-term support for post-disaster recovery. It was claimed that disaster relief provided by hotels and resorts was faster and more effective than the government response.

> "I set up an emergency fund for the villages and collected about AUD 70,000. I used AUD 12,000 to provide food for 1,600 people in the four villages over a period of 12 days. Another part of the fund was used for installing a water reticulation system in one of the villages. In this village women had to walk 4 km to get water from the river, now they walk a maximum of 50 m. With the rest of the money, we built a second classroom for the school." (General manager of luxury resort in northern Efate).

> "The assistance provided immediately and ongoing by the [hotel] industry members to various communities around Efate was extensive and well received. The Government processes took forever with many missing out altogether." (Chairman, Vanuatu Hotel and Resort Association, pers. comm. *via* email).

While short-term relief aid and longer-term humanitarian efforts are laudable, it is questionable whether hotel managers have the necessary knowledge and legal backing to provide effective support. In several interviews, hotel managers stated that the government-imposed duties on donations and did not allow expats to involve in post-disaster response and recovery, ostensibly due to concerns that such uncoordinated relief aid would undermine the work of the National Disaster Committee (cf. Barber, 2018).

> "Expats like me were told that if you provided any help on your own you may face deportation." (General manager of small 3-star hotel in Port Vila).

> "The International School organised donations, but then they had to pay duty for the donations." (General manager of luxury boutique resort in southern Efate).

Interviews and research conversations in several local communities presented a mixed picture of the recovery support that was provided by hotels and resorts. Respondents in some communities praised the resorts for their immediate post-disaster relief effort and contrasted it with the comparatively slow government response.

> "After Cyclone Pam, we received food supplies from [two resorts]. [. . .] This support lasted from March to June. During this entire time, the government came only two times. The first help from the resorts came about 1–2 weeks after the cyclone, and the church provided help after 3 weeks." (Chief's brother during focus group discussion in community).

> "After the cyclone, the other hotels further up [north] came around to each household and provided us with food such as rice, tinned meat, and noodles. They came in their vehicles and stopped at each household and gave out the food supplies. They did this for 2 months." (Women's representative during focus group discussion in community).

Yet other respondents felt that the hotels only provided short-term disaster relief but did not support their long-term recovery. Some contended that hotel managers were just concerned about their own staff, but did not help other members in the communities.

> "We didn't receive much help from the resorts. They gave us some food and water, that's it." (Tour guide in an island community off Efate).

> "[The resort] did not give us any help but maybe it assisted its own staff. It will be difficult to get help from the resort because we have to go through the chief and there is a lot of paperwork to do, and we usually give up before we even try. None of the other two resorts provided help." (Chairman of men's group during focus group discussion in community).

The findings show that post-disaster relief support to local communities by the tourism industry depended on the goodwill of the resort owners who even had to face risk of deportation when they provided assistance. Most resorts provided relief aid to the land-leasing communities only, which is aligned with findings from the disaster response of the tourism sector in Fiji following Cyclone Winston in 2016 (Carrizosa and Neef, 2018). While the motivation for disaster relief support seemed genuinely altruistic, these practices also play a role in providing legitimacy to a foreign-dominated tourism sector.

Recovering Together? Differential Recovery Processes in the Hotel and Hospitality Industry and Among Local Communities

Ten out of the 22 hotel businesses included in our survey suffered moderate to severe structural damages to their accommodations. Another five businesses reported structural damages to lobbies, restaurants, bars and jetties, while their rooms remained structurally intact. Four more businesses suffered from water infiltration in the rooms, which subsequently caused damages to electric appliances, such as air conditioners and fridges. Only three hotel businesses in the survey remained largely unaffected, apart from fallen trees and other minor damages. 12 hotel businesses had to close their entire operations for several weeks or even months, while ten businesses remained fully or partially operational and open for guests.

A recurring issue that was mentioned in the interviews with hotel managers was the lack of government assistance to the tourism sector in the aftermath of Cyclone Pam. The interviewees acknowledged that there was a lack of government funding for the Department of Tourism and the Vanuatu Tourism Office, so their staff did not have the capacity to assist the hotel industry in a meaningful way. Comparisons were drawn with Fiji's tourism sector recovery after Cyclone Winston in February 2016, which was perceived as much quicker and more effective.

> "We got no support from the government. In Fiji, there was a very good tourism recovery program, but here in Vanuatu we had absolutely nothing." (Food and beverage manager at 4-star beach resort in Port Vila).

Several hotel managers mentioned how they had been let down by the insurance companies. Only the larger multinational resorts and some of the luxury boutique resorts reported to have had adequate insurance cover, while most other hotels and particularly the tour operators were either not sufficiently covered or completely uninsured. A tourism survey conducted as part of a post-disaster needs assessment in the immediate aftermath of Cyclone Pam indicated that six of the 38 registered hotels in the capital Port Vila did not have any insurance coverage and that in other parts of Efate less than 50% of the registered accommodation businesses had insurance (Government of Vanuatu, 2015). Many of the smaller hotels and resorts in our survey had continuing legal battles with their insurance company that refused to pay for the damages caused by Cyclone Pam and related sea surges as well as any follow-up damages that were not covered.

> "For the small- and medium-sized tourism businesses it's difficult to recover, as the insurance companies find ways not to pay our damages." (Manager of small 3-star hotel in Port Vila).
>
> "The resort is still in a legal battle with the insurance companies, they are trying everything to not pay our claims." (Food and beverage manager at 4-star hotel in Port Vila).

Most hotel and tour operation managers we interviewed in our survey reported severe difficulties in rebuilding their tourism business. Those that did not suffer any structural damages to their facilities and only needed to do a major clean-up were the lucky ones, as they could provide accommodation for returning tourists, but even more so for the humanitarian aid workers that flocked to Vanuatu following Cyclone Pam. Six out of the 22 hotel businesses in our survey provided accommodation for international relief workers, military personnel and journalists in the immediate aftermath of the cyclone, which reduced their economic losses to some extent. The large influx of these groups of foreign "experts" was another form of "foreignization of space" (Zoomers, 2010) that occurred in the wake of the disaster.

In the immediate aftermath of Cyclone Pam, it was estimated that a total of 300–500 employees would be laid off in the formal economy, most of them employed in the tourism subsector (Government of Vanuatu, 2015). According to our qualitative survey, complete staff layoffs occurred only among tour operators and high-end hotels and luxury resorts. Yet the majority of surveyed hotels in all categories did not lay off any of their staff and also maintained their salaries at the same level. In many cases, the tasks of employees were changed in the aftermath of Cyclone Pam.

> "We were closed for 5 months, but we kept all our staff. We paid them the full salary, but their roles changed, for example housekeeping staff became gardeners. We even hired more people for the clean-up and provided them with meals." (General manager of luxury resort in northern Efate).

Some hotel owners who retained their staff tried to consider the fact that their employees also had to take care of rebuilding their own homes and adjusted the work schedules. Others provided additional support in kind or cash. However, not all employees were so lucky to keep their jobs and get generous support from their employers. Several high-end hotels laid off their staff, particularly those that had sustained so much damage that they remained closed for more than 6 months. Recovery was most difficult for the small heterogenous communities from different islands that had been established around the resorts and were relying to 100% on their income from tourism.

"Most of the staff [that had been laid off] did not find a new job. They just did some gardening, so they had something to eat, but they could not send their kids to school anymore, as they couldn't afford the school fees. The [resort] owner provided some food and clothes, and he continued to pay for the electricity and the water, but other than that he did not help us much." (Receptionist at luxury boutique resort in southern Efate).

Several local tour operators had to lay off the majority of their staff and cut salaries of the remaining employees, as fewer tourists came to Vanuatu in the months following Cyclone Pam, and about 19 cruise ships cancelled their stopover in the country (Government of Vanuatu, 2015). In addition to the adverse impact on employees in the tourism industry, it was estimated that Cyclone Pam affected about 3,600 female micro-entrepreneurs (the so-called "mammas") in all disaster-affected provinces combined (Government of Vanuatu, 2015). Our own observations at local handicraft shops and informal conversations with shopkeepers in Port Vila indicated that their business recovery was very slow, even more than a year after the disaster. Moreover, about 2,100 minibus and taxi drivers suffered severe business disruptions due to damage to road infrastructure and a slump in demand for their services, as tourists stayed away from Vanuatu in the months that followed the disaster (Government of Vanuatu, 2015).

Women played particularly critical roles in the recovery process, as mobilisers of capital, innovators and entrepreneurs (cf. Clissold et al., 2020). Yet, overall, there was a consensus among the interviewed community members that the tourism industry recovered more swiftly than the local communities. Several interviews with Ni-Vanuatu hotel staff also confirmed the uneven recovery of resorts and communities.

"The resorts recover quick time [sic], they are now back in full swing, whereas we are still struggling." (Male participant in focus group in southern Efate).

"The resort recovered much quicker than us in the village. It took us a long while before we were able to harvest from our food gardens again." (Chairman of men's group in community focus group in Port Vila).

"Most of the hotels recover more quickly than ordinary people" (Interview with assistant manager at budget hotel in Port Vila).

Remittances from relatives and friends who lived permanently overseas or were involved in temporary working schemes abroad played an important role in the post-disaster recovery process in some communities. In one of the focus group discussions at community level and in several interviews and research conversations, it was stated that participating in the seasonal workers schemes implemented by the New Zealand and Australian Governments helped in the recovery process of local communities.

TABLE 2 | Visitor arrivals in Vanuatu 2011–2019. Source: Vanuatu Statistical Bureau, 2020.

Year	Visitor arrivals by air	Visitor arrivals by sea
2011	93,960	154,938
2012	108,161	213,243
2013	110,109	240,483
2014	108,808	220,175
2015	89,952	197,471
2016	95,117	256,482
2017	109,170	223,551
2018	115,634	234,567
2019	120,628	135,357

Bringing Tourists Back to Vanuatu and Enhancing Disaster Resilience

Less than 3 weeks after Cyclone Pam struck the islands, the Vanuatu Tourism Office (VTO) started a campaign on social media platforms to regain potential visitors' confidence in Vanuatu as a tourist destination. Under the slogan #VanuatuStillSmiles, the VTO wanted to assure people in the major source countries Australia and New Zealand that Vanuatu was still open for tourists. Despite these attempts to attract tourists back to Vanuatu, Cyclone Pam had a considerable impact on tourist arrivals over the year 2015, when visitor arrivals by air fell well below the numbers of 2011 (**Table 2**). While a slight recovery was recorded in 2016, numbers were still about 14% below the year 2013. Arrivals by cruise ship were also down in 2015, but recovered to a new record level of over 250,000 visitors in 2016. Yet in 2019, visitor arrivals by sea dropped to their lowest level in the 2010s, while visitor arrivals by air grew steadily until 2019.

Some hotel managers suggested that the Department of Tourism should give discounts for travelers, and that more attention should be given to the traditional source countries, i.e., Australia and New Zealand. One respondent also called for more expat expertise in tourism campaigns.

"We need to be pushing interest from Australia and New Zealand, because that is our main market. The Department of Tourism needs to employ an expat to take care of all this promotional work." (General manager of luxury beach resort in southern Efate).

Yet the call for involving more expats in promotional campaigns was challenged by one of the Ni-Vanuatu respondents who expressed her grievance that indigenous citizens and their expertise were often ignored.

"I recently went to a tourism forum which was organized by the Department of Tourism. They presented a report by the International Finance Corporation on cruise-ship tourism and they were talking about challenges and benefits, but there were only expats, no Indigenous people. How can we talk

> about challenges and benefits without involving the Indigenous people?" (Caretaker of 4-star apartment hotel in southern Efate).

The quote above provides evidence that "foreignization of space" (Zoomers, 2010) through an expat-dominated tourism sector is not just a physical-spatial process. It has also strong cultural and political connotations, whereby indigenous citizens' rights to being consulted and actively involved in decision-making processes are increasingly compromised.

Rural communities are now voicing their concerns about the opaqueness of land leases concluded many years ago. Some community members call for a review of the lease conditions.

> "We had demanded in past several meetings to see what the terms and conditions are like in the agreement that was signed back in the 1970s between our chief and the resort lawyer, but no one seems to know if there is any copy available. We wanted to review the terms and conditions with the resort. We do not know what the first conditions were like." (Female elder and journalist during focus group discussion).

One of the interviewed managers suggested that villagers were confronted with issues of land scarcity, as many had sold or leased out their land a long time ago without considering the long-term consequences. He expressed concerns how this would affect their recovery and future resilience.

> "The communities have improved their building infrastructure, so they are now better prepared if another cyclone hits the area. But now they face another challenge and that is the developers that are coming in, mainly for residential development. Many developers have bought land way back, but they are now coming to claim their land rights." (General manager of luxury resort in northern Efate).

This is a particularly concerning development given the crucial importance of land for economic recovery but also its cultural significance. Ni-Vanuatu citizens' strong sense of place attachment is at risk of becoming increasingly undermined by the tourism sector. The exclusionary powers of market, regulation and legitimation (cf. Hall et al., 2011), as exercised by the tourism industry, are likely to remain sources of tension between Ni-Vanuatu and the expatriate community. These tensions will certainly be exacerbated by the current COVID-19 pandemic which has brought tourism in Vanuatu to a near-complete standstill.

DISCUSSION AND CONCLUSION

Susceptibility to tropical cyclones is one of the reasons why Vanuatu is the world's most at-risk country for natural hazards, according to the World Risk Index (Birkmann and Welle 2016). Cyclone Pam's impact on Vanuatu's tourism industry and the thousands of people – Ni-Vanuatu and expats – that depend on the sector was devastating. The majority of hotels and resorts included in our study experienced significant structural damages to their facilities, and many of them had to close for several weeks or even months. While hotel businesses in Port Vila tended to help only their own staff, resorts in rural Efate provided quick and often efficient support to adjacent communities (particularly to those from which they leased the land). However, such spontaneous private sector relief initiatives were not approved by the government. Most hotels and resorts included in our study tried to retain the majority of their staff during the recovery process. Yet, complete layoffs did occur, primarily by the large high-end hotels and some luxury boutique resorts that remained closed for more than a year, as well as the hotel businesses that went into bankruptcy.

Overall, the case of Vanuatu is a stark reminder that customary land tenure is not a strong defense against land deals but can actually be an enabler (cf. Neef, 2021). Many Ni-Vanuatu have lost access to coastal land and near-shore fisheries as a result of foreign investment in the tourism industry and private housing development, and few members in the community can find secure employment in the service sector to compensate for those losses. Although customary land is strongly protected by the country's legal framework and cannot be sold, Vanuatu has experienced a massive boom in the real estate market in the form of long-term leases and sub-leases, primarily for resort development but more recently also for residential tourism projects (cf. McDonnell, 2018). Reduced access to marine resources and coastal land is limiting the economic opportunities for most Ni-Vanuatu who still depend on farming and fishing for their subsistence. Hence, the relationship between local communities and expatriates remains complicated, oscillating between cooperation and conflict.

The results from this study underscore the need to include power relations and the politics of tourism policy making in frameworks for improved disaster risk management in the tourism industry of Vanuatu and other small island developing states. Although the importance of social relations and structures of domination in determining vulnerability has been emphasized as early as the mid-1990s by Blaikie et al. (1994) and further underscored by Wisner et al. (2004), many studies continue to overlook these root causes of vulnerability to hazards. For example, a study by Klint et al. (2012) that analyzed the policy environment for climate change adaptation and climate risk management in Vanuatu's tourism sector, largely ignored issues of power, access to land and politics, instead presenting climate risk policies as a purely technocratic issue. Loehr's (2020) Vanuatu Tourism Adaptation System acknowledges that "land management processes and customary land ownership have an influence on local ownership or participation in tourism businesses" (p. 527) but does not provide any further insights into the inequalities and injustices that the foreign-dominated tourism sector has produced; neither does it mention the importance of continued access to land-based and marine resources for disaster resilience of Ni-Vanuatu coastal communities. By contrast, the Tourism Crises Response and Recovery Plan (2020–2023) developed by Vanuatu Department of Tourism (2020) in response to the COVID-19 pandemic and tourism crisis makes explicit reference to the fact that the "high level of foreign ownership and control" in Vanuatu's tourism sector has contributed "to the dispossession of land" and increased "land disputes within communities," thereby reducing the subsistence capacity of communities and the resilience of the local economy (p. 8).

The aftermath of Cyclone Pam has exposed the volatility of employment opportunities in the tourism sector. Yet the post-cyclone impacts have been dwarfed by the 2020 COVID-19 pandemic that brought the tourism sector in Vanuatu to a near-complete standstill (Vanuatu National Statistics Office, 2020). Many hotels and resorts had to close permanently, while others had to lay off most of their staff and went into temporary hibernation. A luxury resort in northern Efate reportedly discontinued all its community engagement activities (Connell, 2021). Although Vanuatu has had only three cases of COVID-19 (as of September 6, 2021) all of which occurred in quarantine, there is a severe risk that it will take Ni-Vanuatu communities much longer to recover from the economic fallout of COVID-19 than from Cyclone Pam, as many have become dependent on the foreign-dominated tourism sector. To make matters worse, remittances from temporary migrant workers have dried up due to border closures in Australia and New Zealand (cf. Connell, 2021). With many small tour operators and small- and medium-sized hotels and resorts not able to survive this protracted tourism crisis, multinational hotel chains may see opportunities to capitalize on the tourism crisis and scoop up land vacated by smaller businesses (cf. Neef, 2021). Vanuatu's government will need to keep a close eye on such developments if it wants to provide a more level playing field for tourism actors and a more resilient and inclusive tourism economy in the post-COVID-19 recovery process. In a wider disaster risk management context, this study calls for disaster risk governance strategies in the tourism sector that address power differentials and inequalities that are often at the heart of vulnerabilities and compromised resilience.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the qualitative data sets contain information that could potentially identify the research participants. Requests to access the datasets should be directed to AN, a.neef@auckland.ac.nz.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Human Participants Ethics Committee - The University of Auckland. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

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Testing Interscience in Understanding and Tackling Disaster Risk

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Efforts in Disaster Risk Reduction (DRR) are widely geared towards integrating indigenous knowledge and science. Several conceptual frameworks have thus evolved towards co-creating knowledge and co-designing DRR measures from the standpoint of the communities-at-risk. This is claimed to foster optimization and sustainability of measures. This study tests the effectiveness of this standpoint argument based on the case of floods in the Rwenzori, western Uganda, where a mismatch is noted between research, policy, and action. A protocol was developed to stimulate dialogue on knowledge co-creation and co-designing of DRR measures among participants from three stakeholder groups: scientists, policymakers, and communities-at-risk. Beyond convergence on some measures among participants, equitable deliberations were observed among the different stakeholders. This enabled three processes: coalescing some of the proposed measures, the emergence of hybrid worldviews, and co-design of alternative options. The co-designed options fall within the contemporary conceptualization of nature-based solutions and sustainability. This meant that they are adoptable and optimizable over time by communities-at-risk. This constructive knowledge integration and co-design of DRR options were favored by three attributes: coalescing overlaps in theorizations of processes, embracing diversity in ontological values, and self-critiques among policymakers. Lessons are drawn on how these attributes facilitate bridging gaps between science, policy, and action in DRR.

Keywords: disaster risk governance, disaster risk reduction philosophy, disaster risk interscience, hylomorphic framework, standpoint disaster theory

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1 INTRODUCTION

International protocols, driven by the UN strategy for Disaster Risk Reduction (DRR), stress the need to integrate indigenous knowledge with science to suitably tackled disaster risk. The underlying reason is that indigenous knowledge is not only socio-culturally produced by indigenous people—or Communities-at-Risk (CAR). It also has two essential attributes. Firstly, it does provide socio-epistemic insights on the context-specificity of disaster risk (Gaillard and Mercer, 2013; UNISDR, 2015; Bwambale et al., 2021). Secondly, it ensures acceptable and suitable DRR options or interventions by giving weight to community priorities (Mathew et al., 2012; Bwambale et al., 2018). These attributes continue to underscore the indispensable role of indigenous perspectives and practices in DRR. To benefit from and integrate these attributes, scientists and DRR institutions are urged to systematically interact with indigenous people (Gaillard and Mercer, 2013; Ayeb-Karlsson et al., 2019).

The matter of interacting with indigenous people to benefit from indigenous knowledge and to integrate it with scientific DRR has long been investigated. Synthetizing earlier frameworks, Gaillard and Mercer (2013) proposed one consensual approach for integrating bottom-up and top-down actions, local and scientific knowledge, and an array of stakeholders. Re-analyzing the previous frameworks and those post Gaillard and Mercer (2013) and Bwambale et al. (2020) argue that these approaches largely focused on enabling CAR to participate at the content level: i.e., on measures developed by top-down stakeholders (i.e., scientists and policymakers). This would prompt a simplistic commentary role on the part of the CAR; yet little is considered on the salient socio-epistemic processes from the theorization of systematic or repetitive observations among CAR (see also Briggs, 2013). Bearing this gap in mind, the integrated knowledge approach has been extended under the *hylomorphic* framework for integrating knowledge for commensurable DRR (Bwambale et al., 2020). For consistency, this extended integrated framework is, hereafter, collectively termed the *hylomorphic* DRR framework.

In this *hylomorphic* DRR framework, the challenge with DRR is considered as socio-epistemic in the primary sense, and policy in the secondary sense: scientists continue to neglect pragmatic empiricist experiences from CAR and produce recommendations that are disconnected from the real-life context (see also Alexander, 1997; Gaillard and Mercer, 2013). It is these recommendations that are picked by policymakers and implementors. Thus, the *hylomorphic* DRR framework proposes that CAR are involved not only in the content, but also, in the process leading to that content. It emphasizes developing measures from the hybrid knowledge theorization as well as from the standpoint of the CAR (Bwambale et al., 2020). Moreover, debates in this line have led to the coining of the concept of interscience, i.e., integrative science (Van Opstal and Hugé, 2013): it aims to foster co-production of knowledge and a holistic approach to the understanding of—and dealing with—reality (see also Sorrell, 2013). The concept of interscience applies to the *hylomorphic* DRR framework since it aims at coalescing socio-epistemic processes to better understand natural hazards and tackle their consequent disasters through multi-stakeholder dialogue.

Questions remain on the effectiveness of this *hylomorphic* DRR framework in practice since it is yet to be operationalized in enabling the development of suitable DRR measures. This study thus attempts to test this extended knowledge integration framework in a specific context to shed light on its effectiveness. It examines the extent to and/or ways through which it can facilitate the development of suitable DRR options or compromise solutions among diverse stakes. It is based on the specific case of flood DRR in the Rwenzori.

2 THEORETICAL FRAMEWORK

The core theoretical perspective upon which this case study is built is the *hylomorphic* DRR framework as proposed in Bwambale et al. (2020). Insofar as this framework emphasizes aligning science with significant others, especially culture as well as indigenous knowledge, it is a standpoint perspective. Standpoint theorists highlight the potential for indigenous perspectives to expose biases in scientific knowledge. Strong objectivity is thus possible by synthesizing partial overlaps between indigenous and scientific knowledge, weaved and grasped from the standpoint of the indigenous community (Wylie, 2003; Ludwig, 2016, Ludwig, 2017).

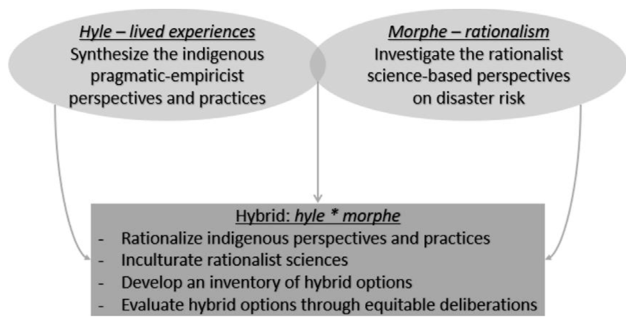

FIGURE 1 | Graphic summary of the *hylomorphic* DRR framework—Adapted from Bwambale et al. (2020).

In the perspective of the *hylomorphic* DRR framework, commensurable DRR is possible if DRR strategies are developed from indigenous standpoints (Bwambale et al., 2020). Here, one of the specific arguments is the claim that the *neo-rationalism* of abstract scientific recommendations contrasts with the *neo-empiricism* of societal values. Unlike the former, the latter, being grounded in indigenous experiences, leads to pragmatic and concrete solutions that consider the sociocultural as well as livelihood needs of the CAR. Additionally, the neo-empiricist aspects are considered as drivers of action as they are part of the way of life of the CAR. In this sense, it is further argued that the sustainable implementation and continued optimization of any measures be determined by how related or distanced the CAR are from the established measure(s). Measures should thus be founded at the standpoint of the CAR through recognizing the substantial unity of lived experience and intelligible scientific understanding of disaster risk. Historical indigenous perspectives and practices should thus be vivified or systematized to expose their explanatory powers. Related global (rationalist) scientific understanding about disaster risk should be inculturated to find a relevant "receptor" to weave into the local socio-cultural context. The "receptor" would be offered by the systematized indigenous knowledge (**Figure 1**).

At the hybrid level, overlapping ontologies can be coalesced for a specific context as highlighted in related literature (Van Opstal and Hugé, 2013; Ludwig, 2016, Ludwig, 2017; Ludwig and El-Hani, 2020). It is thus possible to identify lived experiences upon which specific scientific logic can be applied to provide an intelligible explanation of disaster risk. In the perspective of the *hylomorphic* DRR framework, providing intelligibility to lived experiences individuates the disaster risk science to specific contexts. Doing so, the substantial unity of the rational and the lived reality is achieved, leading to hybrid (context-specific) knowledge theorization that can lead to suitable or adapted DRR options. Over time, this can erase the line between science and indigenous knowledge as well as CAR, thus enabling tacit optimization of the developed DRR options (Bwambale et al., 2020).

With these arguments, the *hylomorphic* DRR framework contributes to three key principles of the suitability of DRR measures (see Bwambale et al., 2020): sustainability, adaptability, and compatibility. Sustainability is viewed in the sense that a measure is designed in such a way that it can locally be maintained and optimized over time to sustainably reduce the recurring disaster. This is possible insofar as the measures align with the culture and worldviews as well as the livelihood of the CAR. Adaptability and compatibility are jointly considered in the sense that a measure can be adjusted to fit into the local culture: measures are most likely to be optimized if they fit within the historical worldviews of the CAR (see also Van Opstal and Hugé, 2013). These elements are possible to mobilize and advocate to negotiate and reach consensus among key stakeholders without any dominating the integration or the process itself. These stakeholders are the top-down actors (scientists and politicians or policymakers) who propel the (neo-)rationalist discourse and CAR who hold discourses based on lived experiences (see also Gaillard and Mercer, 2013).

The assumption in this study is that suitable or compromise DRR solutions will be co-created when lived experiences and rationalist science are hybridized and deliberated on by various stakeholders. Attention is thus paid to what can be learnt, i.e., co-creation or interweaving of knowledge and co-design of DRR options from the interactions of top-down stakeholders with CAR (**Figure 1**). This allows for analysis of several elements: who influences who in the dialogue, how and what informs the influences as well as the context-specific hybrid knowledge and DRR options or strategies that result. The arguments used by different actors in the dialogue are crucial for optimizing this framework and propose ways in which it can best pave the way to develop commensurable DRR strategies.

3 METHODOLOGY: A CASE STUDY APPROACH

3.1 Study Setting in the Rwenzori Region

This study focuses on the case of flood DRR in the Rwenzori region, Western Uganda. A detailed description of the Rwenzori regarding natural hazards and flood disasters can be found in Jacobs et al. (2016a)—see also Eggermont et al. (2009). The Rwenzori is a relevant case study as it is a region where multiple natural hazards co-occur, leading to small but frequent disasters (Jacobs et al., 2016b). Yet there is a mismatch between science and practice that detracts effective DRR (Maes et al., 2018). The Rwenzori is also a region with an established cultural approach and indigenous practices to disaster, which generates resistance to DRR measures imposed by top-down policymakers without consideration for the local context. Moreover, the cultural and indigenous practices, as well as perspectives, are not incorporated in the disaster policy and interventions (Bwambale et al., 2018, Bwambale et al., 2021).

Two additional factors make the Rwenzori interesting for this study. First, it is a region where a recent study highlights the perceived importance of the acceptability of DRR measures by the CAR (Maes et al., 2019). Second, it is also a region in a context of a least developed economy, with limited resources to implement and sustain highly specialized technologies for DRR. Hence, the conceptualization of the *hylomorphic* DRR framework is relevant, to identify what determines the design and consensus-building about the suitable DRR options.

3.2 Synthesizing the Inventory

The point of departure of the implementation of the *hylomorphic* DRR framework is an in-depth investigation of the existing indigenous and scientific knowledge in the study area. This enabled the development of a composite inventory of potential DRR measures recommended by the different ontologies as a basis for deliberations. Based on extensive ethnographic field surveys, indigenous knowledge was investigated in terms of its epistemic nature as well as its understanding and tackling of disaster risk. Attention was paid to reconstructing the historical trajectory of the indigenous perspectives and practices as recommended in Bwambale et al. (2020). In parallel, the state-of-the-art scientific DRR strategies recommended in the study area were also inventoried based on a critical review of secondary data and FGDs. These studies were conducted between late 2018 and 2020 along the three most flood-prone watersheds of South-West Rwenzori (**Figure 2**).

These studies led to a synthesis of 16 key DRR measures. To highlight the factors influencing negotiations, some high-tech DRR measures used in other regions of the globe but known to not be suitable to the Rwenzori context were also included in the inventory: flood-tolerant bridges, weather monitoring system, and dredging. This led to a total of 19 measures, touching areas of Ecological and Hydrological (Eco-hydrological) System Wellbeing, Livelihoods, and Economic Standards, Vulnerability and Exposure Reduction, and Sociopolitical Stability and Responsibility (**Supplementary Appendix SA**).

3.3 Defining and Administration of the Protocol

A protocol was defined to enable evaluations of as well as test co-development of convergence around the 19 different DRR measures by different stakeholders. Notably, only the measures (and not their themes nor their sources) were presented in the protocol.

Participants in this evaluation exercise were drawn from three groups of stakeholders framed along the lines of *Circles of Dialogue*. *Circles of Dialogue* offshoot from the Socratic dialogue which is acknowledged as a method of inquiry. This method is a systematic examination into participants' assumptions, preconceived opinions, principles, and values enabling them to become aware of, and communicate about, "underlying" values. Through this method, participants can arrive at a better understanding of their own values as well as

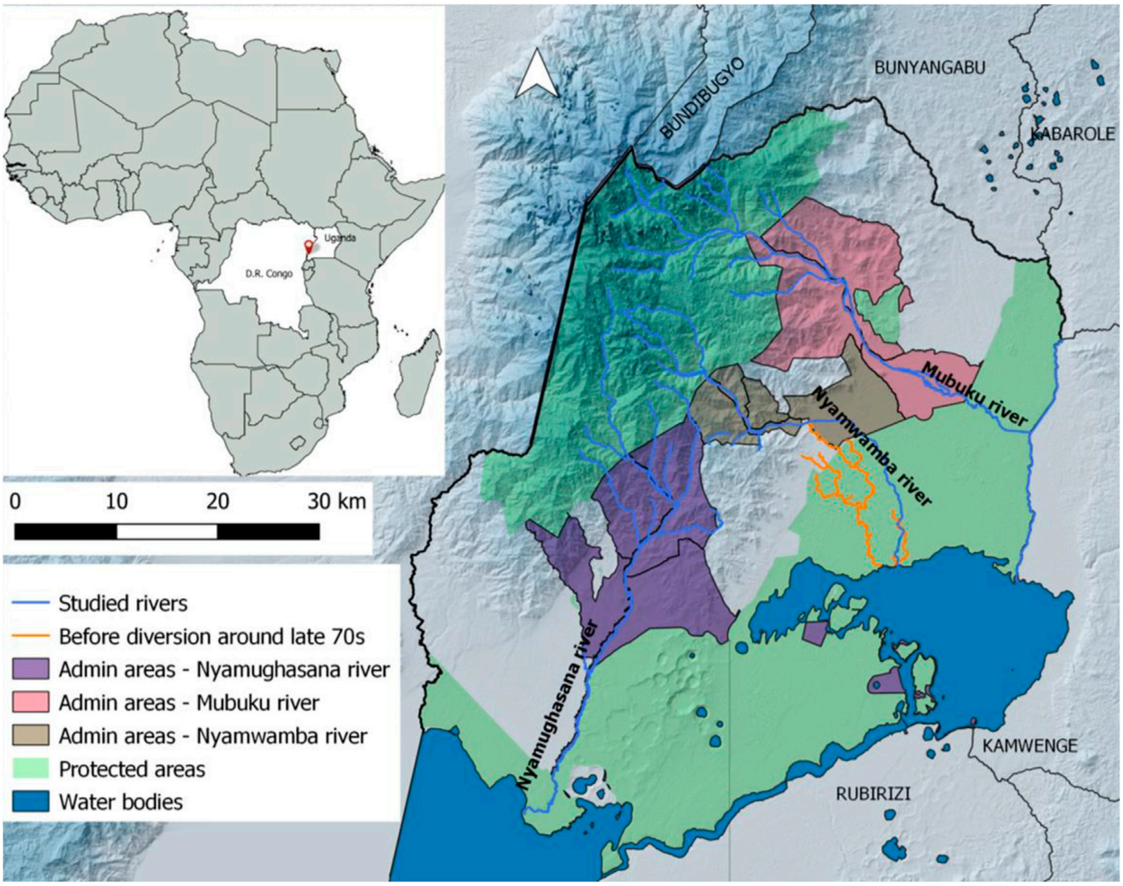

FIGURE 2 | Study area and characteristics in Kasese district, southwestern Rwenzori region. All highlighted are sub-county level administrative areas.

the values of the "Others" (Wortel and Verweij, 2008; Candiotto, 2017; Thomas and Goering, 2018).

In the perspective of DRR, Circles of Dialogue are basically the three key categories that are recognized to have a stake in DRR as well as a mismatch: the CAR, policymakers, and scientists (Gaillard and Mercer, 2013). These categories are, in this case study, respectively represented by: the indigenous practitioners and specialists on flood DRR, representing CAR; the policymakers, i.e., politicians charged with the responsibility of developing and approving policies on DRR under the governmental platform called Disaster Management Committee; and the scientists as well as technocrats or scientific advisers, who inform the policy development and DRR implementation (Maes et al., 2017). The selection targeting representatives knowledgeable of the DRR perspectives within their circles was conducted through a triangulated institutional stakeholder analysis following the methods described in Maes et al. (2019). For the scientists, attention was paid to identifying researchers familiar with the Rwenzori as well as scientists holding technical positions in the district local government. Researchers involved in scientific projects on disasters in Uganda were included. Policymakers and CAR participants were drawn from the cultural and political jurisdictions along the three frequently flooding rivers (**Figure 2**). The protocol described hereafter was administered to the participants in February 2021 through workshops along these watersheds: Nyamughasana (Workshop 1), Mubuku (Workshop 2), and Nyamwamba (Workshop 3).

For exhaustive deliberations, participants were limited to 15, with equal representation from each of the three Circles of Dialogue per watershed. In each workshop, the participants first individually scored each item of the 19 measures. A DRR measure was defined as suitable (+1) if it would be efficient, adapted, feasible: one that can easily be implemented and will be supported and maintained by the community; otherwise, it was scored with a −1 to show that it was unsuitable (**Supplementary Appendix SB**). This evaluation through scoring was not intended to generate quantitative data (for quantitative analysis); but rather, to facilitate the probing of the thought processes leading to the co-creation of knowledge and suitable options among participants during deliberations. Then, participants split into their circles (CAR, policymakers, and scientists) where they deliberated on each item. Each group elected a person to chair the discussions and a secretary to take notes. Each group deliberated on each item based on the definition of a suitable DRR measure but could point out any news views. Thereafter, the circles merged for a discussion between all participants. This formed the phase to observe the negotiation and co-creation process. Here, notes from discussions in the circles were presented to allow for open and constructive debate among all participants regarding the best measures and strategies. After extensive deliberations, the individual scoring of each measure was redone. This was done to check whether participants changed their opinion following the deliberations and co-creation exercise as a basis for follow-up discussions. Follow-up discussions enabled an exhaustive viewpoint on themes that emerged.

3.4 Data Analysis

The NVivo 12 software was used to structure and analyze the collected data. Data were synthesized through analytical induction. This involved identifying and coding recurrent patterns that enable the building of logical categories among stakeholders in the entire process of deliberations. In the context of the *hylomorphic* DRR framework, attention was paid to elements that favored the process of co-creation of knowledge around the proposed measures or new worldviews and co-development of suitable options. Enabling factors in this process were noted as indicators of interscience in understanding and tackling disaster risk. Recommendations on the analysis of qualitative data as proposed in Baxter and Eyles (1997) were followed. These results of this analysis were contrasted with the theoretical framework developed in **Section 2** to highlight the added value of the *hylomorphic* framework. These results are presented in accordance with the format followed in deliberations, i.e., the analysis start with the experiences in the specific Circles of Dialogues, then the deliberation on the knowledge co-creation and co-adapting of the proposed measures.

4 INTEGRATING KNOWLEDGE PERSPECTIVES IN PRACTICE

4.1 Participant Experiences With the Proposed Options

Based on the individual evaluation of DRR measures before interactions between participants, a convergence of positive opinion is observed towards nonstructural and/or less high-tech measures; but also, those that are geared towards social stability and wellbeing. This explains, accordingly, the relatively high scores for measures in the category of Eco-hydrological System Wellbeing as well as Sociopolitical Stability and Responsibility. On the opposite, sharp contrasts between opinions of participants are noted on measures that are not context-specific, i.e., not considering the local socio-ecological conditions of the CAR and/or focusing on high-tech engineering (**Supplementary Appendix SC**).

Additionally, observations and transcripts from workshops revealed the relative position and attitude of groups of actors to each other regarding the proposed measures. For instance, in several cases, scientists not only found the proposed measures interesting; they also discovered that several initial worldviews of the CAR are intelligible. Moreover, when asked to identify the best measures to prioritize and new ones to add, some convergence is suggested in the responses of the different circles (e.g., **Table 1**). These became the point of departure, not only for (re-)rationalization and (re-)contextualization of hybrid disaster risk knowledge; but also, for the re-politicization and negotiation towards the best ways for implementing DRR options among the participants.

4.2 (Re-)rationalization and (Re-) contextualization Foster Hybridization

The recognition of similar as well as new insights from the Circles of Dialogue was observed to spark off equitable contributions to adapt the proposed measures and co-create several new options. This can be illustrated by three key examples. First, while regional weather monitoring and gauging systems were considered unsuitable due to limited budget, the need for an early warning system or a system detecting flood onset was still much desired. Policymakers reported that a system of discharge sensors was installed in the river channel starting in 2015, following the 2013 damaging floods. This was a multibillion investment, funded by the government of Egypt (see Atef, 2017). But these devices were devastated by the subsequent floods, especially the floods of 2020. Besides that, CAR criticize the fact that the sensors only informed about the flood when it was too late. CAR elaborated on how they rather follow the behavior of the rainfall upstream with visual observations, the type of clouds, and duration of rainfall:

> "There is that sort of black clouds. Once we see that and followed by rains for more than 2 hours, you know, we will experience floods. Then communications pass, telling people to move from the valley. You see, we do not even have to wait to see river levels" (Workshop 1, CAR, 2021).

The explanations of the CAR suggested that the timing of the scientific alert based on sensors was less suitable compared to that of their indigenous system to safe crucial property. Borrowing from this, participants theorized the potential to calibrate something that can be used as an early warning system, i.e., based on timing and duration of observed rainfall as well as other local parameters that have been observed through time by the indigenous people to consistently indicate the potential for floods locally. Moreover, as scientists (influenced by the CAR) frequently cited, "*indeed, if we wait for the water to be high in the river to [detect and] send an alert, this is already way too late*" (Workshop 2, Scientists, 2021).

The second example stems from that of dredging of the river channel being perceived as an unsuitable measure. According to participants, even local government has hardly successfully conducted it due to limited prioritization in budget. The proposal from the CAR was to rather train and support gravel and sand miners to conduct their activities in a conservation manner. This, according to the CAR, is an alternative to dredging as it would be sustained since it is also a source of livelihood. Several scientists found this interesting. For instance,

TABLE 1 | Sample viewpoints of participants when asked to prioritize measures among the inventory and add more.

Verbatim viewpoint	References
• We are only trying to make some prioritizations. Otherwise, the proposed measures cover all that we could mention about flood tackling floods along this river. After all, they came from us	Workshop 1, CAR, 2021
• It is interesting to see what the [CAR] have prioritized. At least we agree on some things. I must say, it is difficult to categorize, getting the best preferred [measure]. Most of these things [i.e., measures] are valid. But we tried to prioritize. . .	Workshop 1, Scientists, 2021
• All the protocols are good, and none can override the other. Maybe we just need to prioritize. Now, when it comes to which measures to prioritize, that is where the issues start. That is when you will see 'major generals' [i.e., high-rank politicians who decide on measures in their subjective favors]	Workshop 3, Policymakers, 2021

> ". . .if they are organized, something could be done to build their capacity in contributing to desilting as they get the sand. We can, for instance, train them how to pick sand above the bridge and tell them to [avoid] the sand above the bridge. They just need to be organized, trained and monitored. We are no longer in the protectionism era, now it is conservation" (Workshop 2, Scientists, 2021).

The third example is the conservation approach co-created around several measures: soil and water conservation, riverbank fortification through the water-tolerant trees as well as vegetating buffer zones in the alluvial plain, and reforestation of steeper parts of the catchment. These were frequently considered in the broader sense of land-use planning and as measures affecting livelihoods. For example, scientists argued that soil and water conservation is a good agronomic practice that improves soil fertility and is easy to implement considering that the CAR are largely agrarian communities. CAR concurred with this viewpoint and elaborated that they would have several benefits from it. For instance, "*we get high yields when the soil and water are conserved in the gardens*" (Workshop 1, CAR, 2021). Reforestation was also considered by participants as part of the broader soil and water conservation to support stabilizing soil in the riparian areas and along the watershed. Besides, trees are harvested for livelihood. The same holds for buffer vegetation across the alluvial plain. For instance,

> "Some natural vegetation is culturally planted, e.g., water reeds and bamboo, along the downstream of Nyamughasana river. They are harvested in a conservation manner to ensure that the river is conserved against floods, and the CAR derive their livelihoods. However, this is conducted at a very small scale" (Workshop 1, CAR, 2021).

Moreover, it was convergently agreed that most non-degrading farm Income Generating Activities (IGAs), such as apiculture, would fit within the greened buffers and forested slopes. All these measures are, additionally, considered as crucial to limit silting of the river channel. Here, dredging was perceived to be required in the early stages of implementing such a conservation approach and/or occasionally. Participants indeed jointly theorized that the conservation-based sand mining coupled with conservation-based land use would accomplish the same outcome, thereby preventing the costly dredging. Similarly, the conservation-based land use approach was considered to also replace the need for stabilizing riverbanks with gabions. Gabion construction was several times proposed by CAR but considered unsuitable on technical grounds during the deliberations. Besides, as cited by scientists working in government, the recent gabions constructed by DMCs were funded by the Egyptian donation; there was no plan how to maintain them.

It can be noticed that the co-created solutions are geared towards both nature conservation and the improvement of the socioeconomic conditions or livelihoods of the CAR. Other observations indicate that the extent to which a measure contributes to livelihoods could be influential. For instance, formalizing and supporting Savings and Internal Lending Communities (SILCs) were evaluated as unsuitable. Experience of the CAR revealed that SILCs often have insufficient capital to lend to members for recovery and/or reconstruction in the aftermath of a flood disaster. This is a bit surprising since SILCS are known to support farmers in this region. In a related study, loan portfolios in SILCs groups were found insufficient: some groups could not function properly in the aftermath of a disaster due to the vulnerabilities associated with the disaster, disabling the capacities of farmers to pay back their loans (Maes et al., 2017). Follow-up discussions suggest that SILCs and their element of saving against risk are still at initial stages; they are yet to be studied for their potential to build a financial contingency plan for CAR. Interestingly, scientists viewed SILCS as crucial, e.g., "*. . .they contribute to livelihood diversification, enabling CAR to engage in non-farm income generations and non-degrading farm incomes generation*" (Workshop 1, Scientists, 2021).

In addition to livelihoods, culture and indigenous knowledge came out frequently. Scientists and policymakers, surprisingly, acknowledged that culture and indigenous knowledge have conservation considerations, e.g., planting of indigenous water-tolerant trees. These observations, coupled with the views extracted from the deliberations among participants, can be summarized into four thematic elements: enhancing ecological and hydrological Integrity (across the watershed), diversifying livelihoods, limiting exposure and vulnerability, and social well-being. The elaborations of these themes by participants resonate with that of the measures initially proposed in the

TABLE 2 | Sample key measures linked with the views from the participants regarding key criteria for prioritization.

#	Specific measure	EHI	DIL	LEV	SOW
1.	Reforestation (and enrichment planting) of the upstream and upper slopes of the watershed	x	x	x	
2.	Ensuring natural vegetation along the riparian buffer	x	x	x	
3.	Re-establish and maintain wetlands along the watershed	x	x	x	
4.	Field-based soil and water conservation	x	x	x	
5.	Non-degrading farm IGAs	x	x	x	
6.	Off-farm income-generating activities		x	x	
7.	Supporting rescue teams			x	x
8.	Incorporating indigenous knowledge			x	x
9.	Developing and implementing land use planning		x	x	
10.	SILCs		x	x	x
11.	Mass education on DRR	x	x	x	x
12.	Ensuring and maintaining peace	x	x	x	x

EHI, enhance ecological and hydrological integrity; DIL, diversity and improve livelihoods of CAR; LEV, limit exposure and vulnerabilities; SOW, social and community well-being).

protocol as illustrated in **Table 2** (see also **Supplementary Appendix SA**).

4.3 Re-Politization and Negotiations Towards Best Ways for Implementation

The resultant question from the preceding sections is: *why are (some of) these options not (yet) being implemented?* Results of the workshops' discussions revealed that some (such as reforestation, buffer greening, non-degrading farming) are implemented, but haphazardly at a small scale due to limited resources. Moreover, the situation is compounded by limited extension services: it was evidenced in the workshop that farmers sometimes lack facilitators to train them on the appropriate riparian farming practices specific to tackling floods.

Policymakers and CAR generally concurred on another obvious factor: *the local population generally live a subsistence (hand-to-mouth) lifestyle*. Moreover, as evidenced in the workshops, this subsistence life largely depends on rainfed (and riparian) moisture smallholder farming. This owes to the historical sociopolitical pressures that have left the local population largely disenfranchised and vulnerable (see also Syahuka-Muhindo, 2008). This prevents the large-scale implementation of conservation interventions (e.g., tree farming, apiculture) which take a long time to bring food to the table and fulfill other financial needs at the household level. Hence, scientists emphasized that implementing some measures (e.g., buffering and wetlands as well as non-degrading farm IGAs) might require compensating for the immediate livelihood foregone by CAR. Another alternative is to "*implement these measures in phases or ways that enable meeting the immediate need in the process. . .*" (Workshop 2, Scientists, 2021).

A debate was centered around watershed management including land-use planning to manage floods. Starting from a sort of blame game, policymakers argue that the problem is disrespect of policy; for instance, "*. . .in the 1990s, we used to see the environmental policies implemented and respected. What has happened that this is not the case these days? Are environmental officers still relevant to us?*" (Workshop 1, Policymaker, 2021). CAR respond to this question, indicating that the problem is not the environmental officers, but the politics. For instance, the mismatch is noted between the politicians' desire for votes and community priorities: "*today, when the chief wants to implement [environmental policies], say evicting tycoons defying buffer policy, the politician says, leave those ones. We shall talk to them. He is in fact saying: do not disturb my voters*" (Workshop 1, CAR, 2021). Policymakers confirm these viewpoints, citing issues related to corruption and embezzlement of public funds meant to economically empower the local population, but also lip service politics.

More specific to DRR, questions were raised by CAR on the political motivation of urbanizing floodplains without any flood management practices. Scientists working in the technical division of the local government think that the problem is that evidence-based planning is not yet a central part of governance. This is clearly illustrated in workshop 3:

> ". . .this is not [yet] a knowledge-driven community. All scientific knowledge is for scientists. Often, planning [of infrastructural and social services] is based on political opinions or motivations. In Uganda, scientists are largely involved or used to actualize politically motivated interventions" (Workshop 3, Technical Scientists, 2021).

Interestingly, several policymakers acknowledge these critiques and were moved to think that it is high time to have evidence-based planning. Scientists pointed out that it is however more relevant to focus on what the CAR can do within their means insofar as evidence-based planning and solving of (socio) political hindrances are yet to be achieved. Moreover, several technical scientists attested of being hampered by politics to implement. This is summarized by this quote: "*implementation in this country is very complicated. You want to plan something to do, but the door is locked; you need a key to open, but you do not have the key*" (Workshop 3, Technical Scientists, 2021).

To support evidence-based planning of DRR as well as proper implementation, deliberations were focused on the establishment of an independent unit (authority or committee). This unit would manage the river and flood disasters, but it would also be mandated through the national or central government. This was considered the best temporary option for the current situation. Moreover, as frequently cited, in the current situation it is "*independent authorities [i.e., parastatals] like UNRA [Uganda National Roads Authority] get well funded and work better*" (Workshop 3, Policymakers, 2021). This unit, according to participants, would be composed of members of the CAR, scientific advisors, and policymakers.

5 LESSONS FROM AND IMPLICATIONS OF THIS CASE STUDY

5.1 The Co-Creation Processes

In the perspective of the *hylomorphic* DRR framework, integrating perspectives is centered on converging different theorizations to arrive at a hybrid context-specific body of knowledge based upon which to co-design strategies. This implies integrating the pragmatic empiricist aspects from the CAR (i.e., *hyle*) and the abstract rationalism of science (i.e., *morphe*). This is possible when the two are brought into equal dialogue to cocreate knowledge and best practices as well as devise the best way to implement them (see **Section 2**). The first evidence for this assumption is the consensus reached on some measures proposed under the *hylomorphic* DRR framework (**Figure 1**). This is further attested by the negotiations between the participants in the workshops.

Evidence of co-creation of knowledge and co-development of DRR suitable options is observed in the adaptation of the proposed measures. Specifically, participants were observed to co-create knowledge and co-design suitable DRR options on that would work in situations where some of the proposed measures were perceived as unsuitable. Consider, for example, the elaboration around the potential for designing an alert system based on the parameters that indigenous people have over time consistently recognized as an indicator for intense floods. Interestingly, such hybrid techniques are being noted in other contexts as effective in enabling the local community to avoid damage (Balay-As et al., 2018).

Another evidence of co-creation is elaborated around dredging. While it is found unsuitable, scientists and policymakers craft a strategy based on the suggestion by CAR: sand mining could be used (together with ecosystem-based measures) as a livelihood source to do the job that the costly river dredging would do. The centralization of this co-creation around livelihood is interesting; it evidences the maneuver by CAR in this dialogue through which scientists are grounded into the local dynamics, to understand the driving pressures for certain community activities. Such dynamics are too often neglected in scientific debates.

Another neglected aspect conceptualized in the co-creation is culture at first sight, scientists revealed that they are aware of the critical role of culture through experience. Yet, that was not conceptualized in their debates in their circles. For instance, prior to the intergroup dialogues, several scientists (within their specific circle) still wondered what to do with culture and indigenous knowledge. Consider, for example, this conversation: "*[what] do we with the indigenous opinion or views that have never been verified. When floods come, they will say that the gods are not happy. Maybe [they should be included] just a buy-in that they participated, so that they can easily adopt*" (Workshop 1, Scientists, 2021). This is a typical exemplification of the misconceptions of indigenous knowledge to which some scientists still cling. Often, this is due to the limited awareness of the evidence of the epistemic contributions of indigenous knowledge in contemporary literature (e.g., Ludwig, 2016, Ludwig, 2017; Balay-As et al., 2018). Interestingly, during the deliberations, indigenous people demonstrate their knowledge in understanding and tackling disaster risk, including those where scientists can start from or to which they can affix their model calibrations to produce more adapted technologies. Additionally, the knowledge of the indigenous people exposes historical sociopolitical constraints and factors influencing disaster risk, fostering self-critiques among policymakers. This motivated scientists to not only propose DRR options that are considerate of livelihoods and culture; but also, those that could be optimized by the CAR themselves considering the political hindrances.

The proposal to solve the sociopolitical hindrances on DRR, e.g., through an independent (public-private partnership) unit, is also a maneuver from the CAR. This would solve the current challenges by bringing aboard key stakeholders to enable holistic negotiations and optimization of knowledge and practices that work in real life. The proposed independent unit would also give a formal representation to the CAR, enabling them to take part in negotiating and controlling the implementation of DRR strategies, with continuous attention to their culture. This agrees with what is currently emphasized among some disaster risk researchers: CAR will consider a measure seriously and support its implementation if it considers their livelihood and culture; but also if they have been involved in the design and decision process (Cannon, 2015; Maes et al., 2019).

Livelihood and culture (especially structures and attitudes) are indeed crucial aspects of DRR as found in various contexts elsewhere and other theoretical literature (Cannon, 2015; Hazarika et al., 2016; Hooli, 2016). They are also seen to largely contribute to community-based DRR in which initiatives of the local community are increasingly found indispensable (Ayeb-Karlsson et al., 2019; Shaw et al., 2021). Yet the aspect of culture should not be over-emphasized: in communities with multiple ethnicities, a cultural mindset could cause a setback related to whose culture and/or indigenous knowledge is considered. Maathai (2010) elaborates this when referring to ethnicities as micronations in various countries across Africa. Cultural structures of domination can, according to this author, create a "tribal mindset" at the expense of a nationalistic identity, especially if micronations are antagonistic. Antagonism related to cultural institutions is historical in the Rwenzori since colonial times. Moreover, until now, they are systematically used as political platforms for patronage politics and clientelism all over the post-colonial Uganda (see Sseremba, 2019; Sseremba, 2020).

Bearing this in mind, the question should be, *what causes the embracement of measures when they come through culture*? What

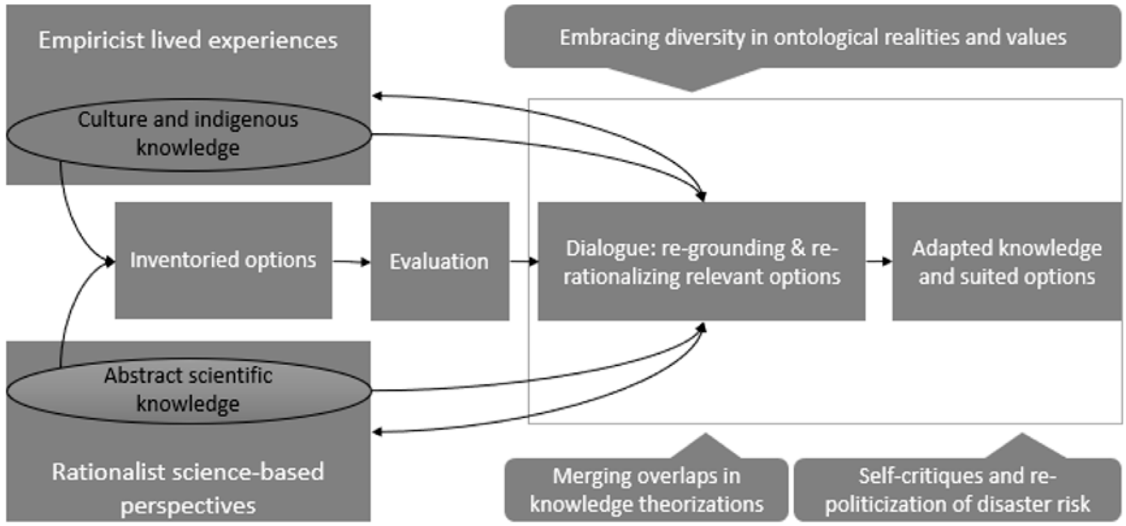

FIGURE 3 | Observed process from inventorying to co-creation of knowledge and co-development of suitable DRR options.

is generally noted is that it is the DRR measures considered to be working on and for the common good of the (local) population that are accepted. Coupled with the viewpoints in the workshops, this can be considered as a matter related to putting local people first in the interventions and giving weight to community priorities. Giving weight to community priorities is often compromised by the capitalist and political pressures of the so-called state-building. In general, however, if these pressures were solved, giving weight to community priorities can improve community embracement (Mathew et al., 2012; Gaillard and Mercer, 2013; Shaw et al., 2021). Thus, it is not only the missing link with culture; but also, with a people-centered development. The central elements are on the needs of the people, which is consistent with the view that DRR be linked with human development (Zakour and Swager, 2018; Raikes et al., 2021).

5.2 Fundamentals of the *Hylomorphic* Disaster Risk Reduction Framework and Beyond

Beyond evaluation and co-creation of knowledge as well as suited DRR options, convergence is also observed on core principles and assumptions for substantial DRR. Specifically, in the perspective of the *hylomorphic* framework, a measure is adopted, optimized through time and lead to substantial DRR depending on how the CAR are distanced or related to it. Here, the key elements described in **Section 2** are related to adaptability as well as compatibility which together are ingredients of sustainable DRR options. These are broadly evidenced not by focusing the evaluation and co-creation around the culture and livelihood; but also, with the contextualization of the (culture and livelihood) around ecosystem-based and social well-being (see also **Table 2**). *What enabled this convergence?*

Firstly, a collaboration of overlapping knowledge theorizations on DRR was observed; for example, in the elaborated consensus around the potential to use observed flood precursors identified by CAR. Secondly, there was an embracement of difference in ontologies and attached values, e.g., embracing the cultural beliefs insofar as they are (riparian) conservation-based and/or enable implementation. These first two led to the shared (hybrid) knowledge theorizations. Thirdly, there is self-critiquing, especially among policymakers based on the political ills unearthed by CAR. This third factor further enabled equitable deliberations among participants: i.e., space was opened for debate, enabling the pointing out of real issues at hand and considering disasters as matters of concern. This, in the perspective of some recent related literature, is a requirement to create a platform for negotiations to arrive at adapted DRR options (Delima et al., 2021). Indeed, it further fostered the adaption of the developed shared knowledge and options at the overlap of science and indigenous knowledge. In other words, the deliberations in the workshops can be summarized to have moved from evaluation through the selection of relevant options to re-grounding as well as re-rationalizing each relevant option. This process, although based on the proposed measures, affirms the position that scientific DRR recommendations are but rarely a given. It is a matter of concern requiring socio-epistemic processes or negotiations to arrive at the most suited options (**Figure 3**).

The core options arrived at in the deliberations (i.e., the ecosystem-livelihood approaches), are in line with two contemporary conceptualizations: Nature-Based Solutions (NBS) and Sustainability. The conceptualization of NBS is aimed at a holistic approach that links social and environmental challenges and opportunities sustainably and cost-effectively. It takes into consideration the contribution of nature to people and vice versa, thereby making it possible to outcompete degradation motives (Fernandes and Guiomar, 2018). This, in the perspective of sustainability science, is possible when the primacy of a systems approach is considered. This means transcending disciplinarity, embracing the diversity of ontological aspects to derive knowledge theories that bridge the natural and social aspects of reality, thereby leading to adapted options (Van Opstal and Hugé, 2013). This, moreover, is linked with four key priorities in and/or around which the proposed measures were grounded: Ecological and Hydrological Integrity, Diversifying and Improving Livelihoods, Limiting Exposure and Vulnerabilities, and Social and Community Well-being (**Table 2**).

The question remaining here is: how does this NBS conceptualization and Sustainability enable or enhance optimization of measures in the perspective of this *hylomorphic* framework? For this case study, the focus around culture and indigenous knowledge on scientifically sound options is interesting. It means that it is possible to erase the line between the lived experiences of the CAR and science. This could favor limiting the mismatch between the rationalist and empiricist discourses. Consider, for example, the NBS cocreated around soil and water conservation, reforestation, livelihood, land use, and non-degrading income generating activities. These are scientifically sound interventions, but which meet with the aspirations of the local population apart from the means to have them started. They are avenues to foster optimization over time.

Another assumption is that if nature is continually observed as a source of livelihood and cultural nourishment, it would incessantly foster the desire for conservation (Bwambale et al., 2018). This assumption has yet met a series of criticism dating from historical debates about human capitalist motives and natural source exploitation (Maathai, 2010). Moreover, in other contexts, the nature of the incentive from nature determines which resources to conserve. For instance, one of the recent studies is on the role of trees in mitigating flood disasters (Tembata et al., 2020): coniferous trees having higher economic and wood value, yet less effective to prevent floods, tend to be preferred against broadleaf and mixed forests in afforestation by policymakers. This implies that effective implementation of the suited options can be compromised by the dynamics related to the market. Accordingly, considering the economic incapacities at the local levels, applying adapted strategies lies in the commitment of the state to provide subsidies that can enable the implementation of the suited yet less marketable options.

The self-critiquing exhibited by policymakers is a crucial part of advocacy, especially by CAR, not only for DRR measures; but also, for systematically adapting them, over time, as political pressures inhibiting them are brought to the spotlight. It helps to reconcile the priorities of all key stakeholders. Besides, CAR have influential knowledge keepers and practitioners. They were cited during field reconnaissance in the CAR: They were acquainted with the indigenous perspectives and practices as well as related to concrete historical dynamics to favorably deliberate with scientists and policymakers. This explains the observed re-rationalization as well as re-contextualization of each of the selected options during deliberations (**Figure 3**). This suggests that local people are likely to favorably participate if their perspectives and practices, as well as worldviews, are equitably presented among the items on the agenda of discussion. Moreover, the core criteria that DRR options be supported and/or maintained by the CAR played a key role in (re) focusing the dialogue to context-specific standpoint. Interestingly, this unearths aspects that scientists are unaware of and the co-creation of hybrid solutions by all participants. This highlights the potential for multi-stakeholder consensus on the people-centered DRR approaches. It is indeed at this stage that the priorities of local people and scientists, as well as policymakers, can be reconciled. This shows the centrality of standpoints. Several scholars had alluded to the view that meaningful engagement of indigenous people requires skewing the discourse on disaster risk reduction to the standpoint of CAR (Gaillard and Mercer, 2013; Cannon, 2015).

6 CONCLUSION

Synthesizing several prior research on integrating knowledge, Bwambale et al. (2020) argue that: "*indigenous and scientific knowledge perspectives grasp partial realities of the disaster risk [at the local context], ...they should [thus] be integrated.*" Integration would be possible by synthesizing the (pragmatic) empiricist lived experience with the rationalist scientific perspectives through the *hylomorphic* DRR framework. Contrasted with standpoint theories, this framework enables developing a composite knowledge theorization that can lead to adapted options for DRR. In this case study, the implementation of the proposed framework demonstrates how to facilitate a consensus on a set of DRR options that is nearer to the local context. This is done by investigating the empiricist and rationalist DRR knowledge. Suitable DRR options are optimized through dialogue, sharing of knowledge, and co-creation of more adapted options. In the dialogue, progress is noted from simple evaluation of the proposed measures to deliberations for co-creation of those that are considerate of the specific context. The knowledge and options arrived at in the co-creation process highlight the convergence between the different stakeholders involved. This is noted to be influenced by three key aspects: the ability to merge overlapping epistemologies, accepting diversity in ontological realities and values between scientists as well as policymakers and indigenous people, and self-critiquing which opened space for negotiations on the best ways towards DRR. This process suggests that DRR options cannot be considered as a (scientific) given, but a matter requiring socio-epistemic processes or negotiations. The resultant convergences and co-creations were found to be centered around ecosystems-based management of the floods, but also considerate of livelihood and embracing the role of culture. Implementation of such DRR options will however depend on the willingness of policymakers to foster specific nature-based interventions, e.g., supporting implementation of non-market oriented DRR solutions through offering some subsidies.

These findings are largely explained by skewing the discourse to the aspirations of the CAR in accordance with the *hylomorphic* framework. It can thus be argued that this framework is not only crucial for arriving at suited approaches; it also evidences the viewpoint held in the vulnerability paradigm of DRR, that standpoint matters in developing measures and strategies that would be appropriate to the local context. Further studies will increase understanding of its effectiveness in integrating knowledge, identifying, and implementing substantial DRR.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

BB: Conceptualization, methodology, formal analysis, and writing—original draft. MK: Conceptualization, methodology, writing—review and editing, supervision, and funding acquisition

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SUPPLEMENTARY MATERIAL

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Assessment of Top-Down Design of Tsunami Evacuation Strategies Based on Drill and Modelled Data

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Tsunami evacuation drills are helpful tools aimed at reinforcing procedures and practices to reduce disaster risk, especially for vulnerable populations like school-age children. While the predictive value of evacuation drill data has been pointed out, challenges exist in enhancing the scientific examination of this information, with the final aim of improving proactive preparedness and scenario-based evacuation strategies. We address this gap by delivering a mixed-method approach that combines ground-collected data and tsunami and evacuation computer-based modelling, using as a case study the evacuation drill performance of four K-12 schools in the cities of Valparaíso and Viña del Mar, Chile. Our main objective was to critically assess the efficacy of the drill-based evacuation procedures of the schools by comparing them in the light of a likely worst-case tsunami scenario (based on historical data from the 1730 event) in these areas. Our findings show that, although a large number of evacuees from the schools could rapidly achieve evacuation to safe locations, complete evacuation (that is, 100% of evacuees reaching the shelter) is only achievable if the Evacuation Onset Times (i.e. the time, relative to the earthquake, of the first evacuee departing from the school) are shorter than demanding threshold values (between 4 and 14 min), as the result of the tsunami's short arrival time and rapid inland penetration. Hence, we suggest complementing existing national-level protocols with a more detailed, case-by-case management approach, comprising a more precise tsunami inundation modelling and a focus on the characteristics of each of the schools (relative to the student body composition such as age and others, the staff, and the geomorphological conditions of its location). Moreover, we suggest that tsunami evacuation drills in Chile pose significant research opportunities yet to be fully grasped.

Keywords: tsunami, evacuation, agent-based modelling, schools, drills

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INTRODUCTION

In tsunami-prone countries, timely evacuation is the most important and effective method to save human lives (Shuto, 2005). This is especially relevant in countries where the lag time between tsunami generation and first arrival can be as short as less than 10 min (Fritz and Kalligeris, 2008; Williamson and Newman, 2019). This has been evidenced in Chile, where recent earthquakes in Pisagua (2014) and Illapel (2015) triggered tsunamis with arrival times shorter than 15 min (Catalán et al., 2015; Aránguiz et al., 2016). These short times severely constrain the response of the population exposed to this hazard, where school-age children (i.e., persons aged 18 and younger) are particularly vulnerable, due to several reasons. It has been shown that very young populations have higher mortality rates in tsunamis as the result of difficulties related to reduced mobility and low pedestrian velocity that compromise their evacuation capacities (Birkmann et al., 2010; González-Riancho et al., 2015; Yun and Hamada, 2015; Latcharote et al., 2018). Buchmüller and Weidmann (2006) estimated that kids age five and under walk at an average speed of roughly 0.6 (meters/second), which is less than 40% of that of a person in his/her late teens. Additionally, Peek (2008), under a broader disaster-related perspective, points out that infants and young children are physically vulnerable to disasters due to their dependence on adults. On the other hand, older children and adolescents (while also at risk for injury or death) can also develop behavioural, psychological, and emotional issues during and after a disaster.

One widely established way to strengthen preparedness is to conduct evacuation drills to reinforce procedures and practice (UNESCO/IOC, 2020). However, tsunami evacuation drills are frequently criticized for their limited participation levels and other aspects, including the need to halt daily activities, the possible creation of unpleasant feelings in residents and tourists, and the impossibility of reflecting the real state of stress of the evacuees (Mas et al., 2013; Poulos et al., 2018; Sun and Yamori, 2018). Nevertheless, they can be a useful tool to reduce the population's vulnerability. They allow to test the feasibility of the tsunami evacuation plans and highlight possible flaws (Mas et al., 2013), and also to familiarize exposed populations with the hazard, therefore contributing to timely evacuations and less human casualties (Løvholt et al., 2019). Moreover, they do appear to contribute to reducing evacuation times (Vásquez et al., 2018). In consequence, pupils and staff from schools in floodable areas are required to participate in training as a well-established disaster prevention education activity. Furthermore, drills aim at developing "the practical attitude and ability of children for safe evacuations and the willingness to act for the safety of other people, groups, and communities at home and in the community, at the time of disaster" (Oka et al., 2020, p.279). In tsunami-exposed countries like Chile, the authorities periodically carry-on evacuation exercises, some of them exclusively aimed at educational institutions.

School drills also offer research opportunities. They comprise, for instance, active research to grasp non-experts' perceptions and actions, with the final aim of improving proactive preparedness and scenario-based evacuation strategies (Nakano et al., 2020; Sun, 2020). Also, Vásquez et al. (2018) examined a tsunami drill in Iquique, Chile, to unveil a range of issues that might impact the actual evacuation behaviour during an emergency, such as the information provided by the families of the pupils, which in some cases could be contradictory with the school evacuation plan. Poulos et al. (2018) used a training tsunami drill of a K-12 (kindergarten to 12th grade) school in Iquique, Chile, to validate an agent-based evacuation model of the buildings of the school, using video analysis of the actual behaviour of the pupils during the exercise. Oka et al. (2020) point out that while children tend to participate passively in evacuation drills, real disaster response evacuation requires active and practical decision-making. Therefore, they suggest using Information and Communication Technology Equipment (ICTE), specifically tablets equipped with planar maps and street view applications, to increase the effectiveness of in-classroom training for subsequent street evacuation.

The above studies focused on subjective assessments or specific data sources. On the other hand, Sun and Yamori (2018) underline the predictive value of evacuation drill data. However, they also point out that there is a lack of scientific examination of this information, which could be enhanced through information technologies, including Global Positioning Systems (GPS) and simulation models. These technologies can also help people to understand and manage tsunami risk information effectively. Nevertheless, integration between information technologies and tsunami evacuation drills is scarce (Sun and Yamori, 2018). For instance, challenges remain on using these technologies to critically assess the actual significance of tsunami evacuation drills as a disaster prevention strategy, given different hazard scenarios. This gap is crucial in schools, where particularly vulnerable people gather and spend several hours a day. Therefore, this paper aims at providing a significant contribution to this research area by delivering a mixed-method approach that combines fieldwork data and tsunami and evacuation computer-based modelling. We used as case study the evacuation drill performance of a group of K-12 schools in the cities of Valparaíso (33°02′50″ S, 71°36′46″ W) and Viña del Mar (33°00′55″ S, 71°33′00″ W), Chile. Our main objective was to critically assess the efficacy of the drill-based evacuation procedures of these schools, by comparing them in the light of a likely worst-case tsunami scenario (based on historical data from the 1730 event) in these areas. In turn, these findings might support an evidence-based review and enhancement of current disaster risk policies and emergency response practices not only in these two cities, but also in other Chilean, South American and global tsunami-prone communities.

The article is structured as follows. **Section 2** introduces the methodology, including the examined evacuation drill and schools, and describes the modelling approaches. **Section 3** delivers the research outcomes, which we discuss in **section 4**. Lastly, **section 5** addresses the main conclusions of the paper.

MATERIALS AND METHODS

The Tsunami Evacuation Drill on September 5, 2019

The Valparaíso region in Chile (where the city of the same name and Viña del Mar are located) is an earthquake- and tsunami-prone territory, struck by destructive near field earthquakes in 1,575, 1,647, 1730, 1822, 1906 and 1985 (Lomnitz, 2004). Among these, the July 8, 1730, Mw 9.1–9.3 event triggered a destructive tsunami (Carvajal et al., 2017). Klein et al. (2017) suggest that the persistent 300 years long gap between mega-earthquakes in this area might be filled soon by a large seismic event, which in turn could trigger another destructive tsunami. Since 2010, the local branch of the Chilean Emergency Management Agency (OREMI and ONEMI, respectively, by their Spanish acronym: Oficina Nacional de Emergencia del Ministerio del Interior y Seguridad Pública) carries out disaster prevention in this region, comprising recurrent tsunami evacuation drills, aimed at fostering a self-care and prevention culture across the population (ONEMI, 2014a). This approach is part of the risk management strategy ruled by the National Civil Protection Plan, passed on March 2002 by the Chilean government, which establishes general guidelines that are applied nationwide with little local variations, if any. Recently, drills have been conducted in the Valparaíso region one each year in 2012, 2013 and 2016. ONEMI enacted the latest training exercise on September 5, 2019, at 11:30 AM. As in the rest of the country, this emphasis on evacuation aims at fostering community-based education and awareness, the importance of which was demonstrated during the 2010 tsunami, where the tsunami arrived before official warnings reaching the population (Fritz et al., 2011).

Nearly 207,060 people and roughly 200 schools from 19 municipalities participated in this recent drill (ONEMI, 2019). Prior to it, an information campaign through the written and internet media informed the population about the drill's date, but the exact timing was not announced beforehand, except notifying it would occur during morning time. To trigger the evacuation, ONEMI sent a text emergency announcement to smartphones which resembled the newly implemented (in this region) SAE (Sistema de Alerta de Emergencia/Emergency Alert System) messaging system. At the same time, coastal klaxon alarms (where available) sounded. The population used demarcated evacuation routes to access previously designated safe assembly areas, each located at an elevation of at least 30 m a.s.l. These were open-space shelters which could accommodate numerous people, who could reach them by following the street network on foot. Most of these locations had been defined several years prior by the local emergency management departments (with ONEMI's support) using as reference the official tsunami charts developed by the Chilean Navy Agency (SHOA, 2012), which are based on a deterministic hazard assessment using the historical scenario of 1730, albeit with its prior estimated magnitude of Mw 8.8. The magnitude has been updated recently to Mw 9.1–9.3 by Carvajal et al. (2017).

Collecting Drill Data From Schools

During the 1730 Great Valparaíso Earthquake and Tsunami Commemoration (July 8, 2019, 2 months prior to the drill), tsunami awareness seminars were given by local scientists at several schools (Zamora et al., 2020). We chose four of these schools for analysis during the evacuation drill according to their exposure, giving greater weights to highly tsunami-exposed areas in lowlands. Two of them are in Valparaíso: Escuela Grecia (G) and Liceo Matilde Brandau de Ross (MB), and two in Viña del Mar: Colegio María Auxiliadora (MA) and Colegio República de Colombia (RC). These schools are located at 500, 200, 800, and 800 m from the coastline, with elevations of roughly 6, 4.5, 6, and 7.5 m.a.s.l (respectively). Moreover, according to our tsunami flood model explained in **section 2.3**, the expected inundation depth at these schools' locations could be as high as 1.1, 2.9, 3.6, and 3.4 m, respectively (see **Figure 1**). To assess the performances of the schools during the drill, we assigned at least two examiners to each of them. One was in charge of tracking and recording (using video cameras and GPS devices) the trajectory of the first evacuee (henceforth called "head") belonging to the first evacuation group of pupils, from the school gate to the designated safe assembly area. Concurrently, the other examiner did the same with the last pupil of the closing group (henceforth called "tail"). In addition, before leaving with the back of the group, we recorded the departure time of each pupil to assess the evacuation rates. We analysed this GPS data in Google Earth Pro and QGIS systems to establish the performance metrics of each school, required as inputs for an agent-based model (described in **section 2.3**).

The location of the four examined schools and their target routes are shown in **Figure 1A**. **Table 1** shows the collected data during the drill, including the counted evacuees (i.e. number of pupils involved in the exercise), the time lapse between the departure of the head and tail pupils, the total evacuation time, the total distance, and the average evacuation speed, for five different cases. We measured the first four of these according to the percentage of completion of the evacuation trajectory: 25% (v1), 50% (v2), 75% (v3) and 100% (v4). Similarly, we calculated the fifth evacuation speed (v5) as the ratio between the accumulated distance and the accumulated time, from the start until the DEM slope reached 3° (i.e. the threshold where the gradients of the routes become significantly steeper, as shown by **Figure 2**). The objective of this approach was to assess the fluctuating impact of the terrain slope on pedestrian evacuation speeds, as shown by Tobler's basic hiking function (1993). Hence, we used speeds v1 to v5 as inputs for the evacuation model explained in **section 2.3**.

It is also noticeable (as shown in **Figure 1B** and **Figure 1E**) that in MB and RC schools the head and tail pupils took different evacuation routes. Additionally, **Figure 2** shows the gradients of the measured paths of the head pupils in Valparaíso and Viña del Mar, which reveal that final destinations were located farther above the 30 m elevation contour. **Figure 3** shows the number and percentage of departed pupils after ONEMI issued the evacuation warning. In the four examined schools, the first counted persons began to evacuate roughly one or 2 minutes following the warning. The lapse between the head and tail pupils varies from 3 min (MB school, 267 pupils counted) to 5 min and 40 s (MA school, 826 pupils counted).

Agent-Based and Tsunami Flood Model

We aimed to accurately simulate the evacuation trajectories of each school to support subsequent integration with tsunami inundation scenarios. To do this, we further adapted the agent-based model developed by Arikawa (2015) and extensively described in León et al. (2020). This model couples a dynamic bottom-up evacuation simulation of the population (where each individual is represented by an 'agent') with a single tsunami inundation scenario. Using as inputs the initial positions of the agents, their assigned evacuation routes and their walking speeds (which in our simulation can be affected by the terrain

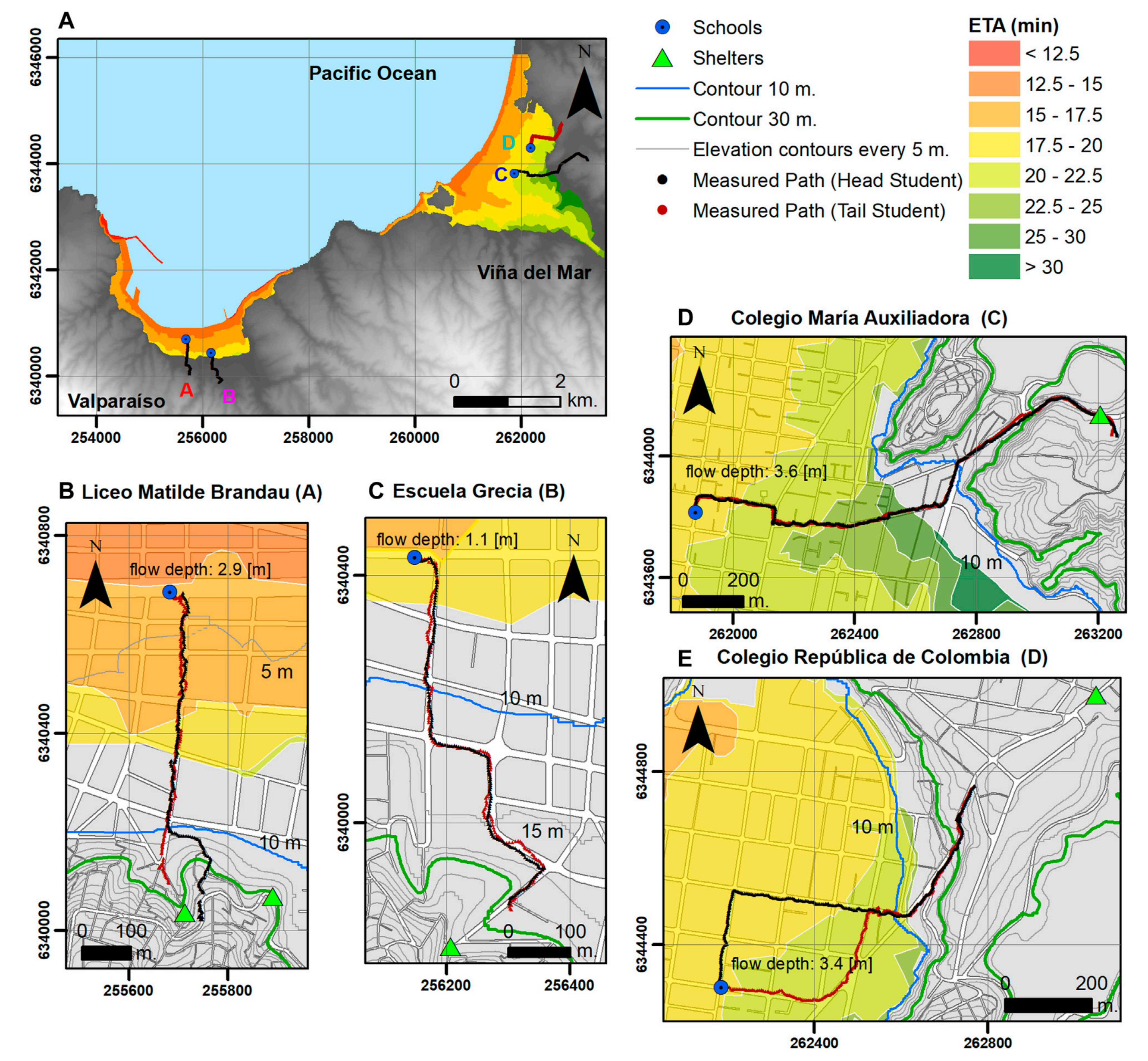

FIGURE 1 | Study areas in Valparaíso and Viña del Mar, including the estimated tsunami inundation area and arrival time, and the location of the four examined schools, their estimated inundation depths and their evacuation routes.

slope), the model updates at each time step (1 s) the agents' locations. Then, it compares these with the inundation data to update the agents' status: 1) moving (i.e., alive but not yet in the shelter) 2) affected (i.e., reached by the water), and 3) escaped (i.e., alive in the shelter).

To validate this model usefulness to simulate each school's performance, first we developed two separate evacuation sub-models for every school, simulating only the head and tail pupils, respectively. For each sub-model, the input data included the evacuation route (with real-world street width and terrain slope) and evacuation speeds v1 to v5 (measured with GPS during the drill), which we examined with and without the impact of terrain slope on them. Then, we used QGIS and MATLAB to spatialize and display each sub-model's outputs and compare them with real-world data. Results showed good agreement (see **Figure 4**), allowing us to subsequently use the agent-based model to simulate the whole group of pupils' evacuations for each examined school, in case of a catastrophic tsunami scenario.

Using the drill GPS-collected data as input, we modelled a range of evacuation scenarios for each school, comprising all the pupils (agents). We considered two routing options, head and tail, and five possible pedestrian speeds (v1 to v5). We also considered varying Evacuation Onset Times (EOT), from 0 to 20 min. These indicate the time, relative to the earthquake, of the first evacuee

TABLE 1 | Synthesis of examined schools in Valparaíso (G and MB) and Viña del Mar (MA and RC).

Name	City	Location	Number of pupils involved in the evacuation drill	Examined pupil	Average evacuation speed/25% of the trajectory (m/s)	Average evacuation speed/50% of the trajectory (m/s)	Average evacuation speed/75% of the trajectory (m/s)	Average evacuation speed/ 100% of the trajectory (m/s)	Average evacuation speed/3° slope limit (m/s)	Total evacuation time (sec.)	Total distance (m)	Time lapse between head and tail pupil (sec.)
Escuela Grecia	Valparaíso	33°02′50″ S, 71°36′40″ W	267	Head	1.31	1.25	1.37	1.34	1.35	553	742.0	192
				Tail	1.31	1.23	1.2	0.99	1.18	808	803.7	
Liceo Matilde Brandau de Ross	Valparaíso	33°02′41″ S, 71°37′00″ W	267	Head	1.44	1.49	1.42	1.14	1.48	720	821.9	180
				Tail	1.42	1.33	1.35	1.15	1.2	614	705.0	
Colegio María Auxiliadora	Viña del Mar	33°01′06″ S, 71°32′59″ W	826	Head	1.39	1.37	1.35	1.25	1.40	1,465	1837.5	340
				Tail	1.09	1.17	1.17	1.11	1.16	1,543	1718.4	
Colegio República de Colombia	Viña del Mar	33°00′49″ S, 71°32′46″ W	606	Head	1.02	0.95	0.92	0.85	0.94	1,239	1,055.0	338
				Tail	1.39	1.19	1.01	0.94	1.07	1,051	987.2	

departing from the school. After this, the departure rate of the other agents is the one shown in **Figure 3**. Lastly, we also tested the model with and without considering the impact of terrain slope on evacuation speeds.

The Chilean coast is exposed to catastrophic, large-scale tsunamis, as it occurred in the 1960 Valdivia and 2010 Maule events (triggered by Mw 9.2 and Mw 8.8 earthquakes, respectively) (Fujii and Satake, 2012). In line with this possibility, we coupled each of the school evacuation simulations with a worst-case known tsunami inundation scenario for the Valparaíso-Viña del Mar area (similar to the 1730 Great Valparaíso Earthquake and Tsunami), as described in León et al. (2019) (whose inundation area is shown by the estimated arrival times (ETA) in **Figure 1A**). This scenario, developed in the Storm Surge and Tsunami Simulator in Oceans and Coastal Areas (STOC) simulator (Tomita et al., 2006), used as an initial condition an Mw 9.1–9.3 earthquake offshore Valparaíso (Carvajal et al., 2017). The model shows that the tsunami arrives at the coast in roughly 12.5 min after the earthquake occurs, reaching the MB and G schools in 15 and 17 min, respectively, while MA and RC schools are flooded in 19 min. In Valparaíso, the waters penetrate inland up to 750 m, while in Viña del Mar the maximum inland penetration reaches approximately 800 m in the urban area and 3 km along the Marga-marga Creek. See **Figure 1** (a).

The coupled inundation-evacuation model allowed us to estimate the feasibility of the drill-based evacuation procedures to escape the incoming tsunami, as it delivered a time-dependent count of moving, affected, and escaped agents.

RESULTS

Figure 5 and **Figure 6** show a synthesis of the temporal evolution of the escaped and affected agents, combining (for the head and tail routing scenarios) the results of 10 simulations (i.e. five evacuation speeds and two cases: with and without considering the impact of the terrain slope on them), for different EOTs. Overall, in the case of short EOTs (2–4 min, which imply an almost immediate departure after the earthquake has finished), if the performance of each school is like its drill head pupil, it is possible to rapidly achieve complete evacuation (that is, 100% of evacuees reach the shelter). This means that, after the first agent has arrived at its safe destination, it takes roughly another 5, 10, 12 and 15 min (in the case of G, MA, MB and RC schools, respectively) to complete the evacuation process. In the case of performances like the tail pupils, for these same EOTs, evacuation completion takes longer in the case of G school (around 7.5 min), while RC school maintains the same 15 min and MB school reduces to 5 min (probably due to the change to a shorter route, see **Figure 1B** and **Table 1**). MA school, in turn, can reach only up to roughly 58% of escaped agents, as the rest would be reached by the incoming tsunami.

If EOTs extend, it becomes progressively hard to achieve full evacuation. For instance, it is also interesting to see in **Figure 5** and **Figure 6** that EOTs above 14 min might rapidly lead to 100% of affected evacuees, for both the head and tail routing options. In

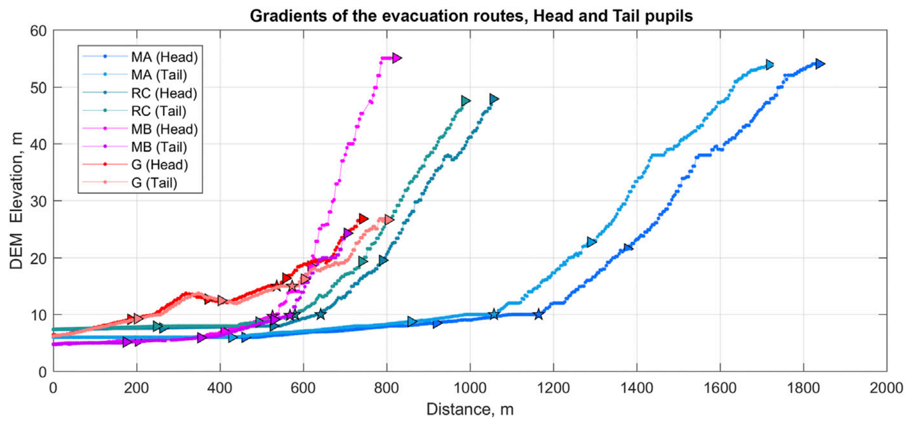

FIGURE 2 | Gradients of the evacuation routes of the four examined schools.

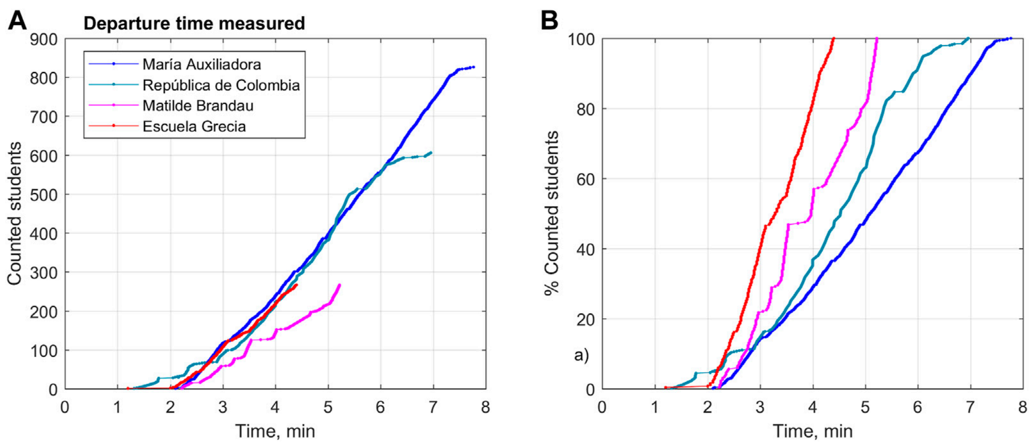

FIGURE 3 | Departure time of the four examined schools.

this respect, as **Figure 7** and **Figure 8** show, full evacuation can only be achieved if the schools begin to evacuate no more than 14 (G), 10 (MB), 8 (MA) and 3 min (RC) after the quake, respectively. If evacuation begins after that, the percentage of affected evacuees rapidly increases according to every added minute of delayed departure, for example to roughly 30 and 75% in the case of G school (tail route). This case might not be significantly dependent on the examined evacuation speed, as it shows little dispersion on the rate of affected evacuees. On the contrary, the percentage of affected agents in RC school (tail route case) varies between 5 and 80%, with an average of 50% (EOT = 9 min).

Critically, there is a threshold time beyond which 100% of evacuees will be affected: 17–18 min for G school, 14–15 min for MB school, 15 min for MA school, and 11–14 min for RC school. These large percentages of affected evacuees are the outcome of the short arrival time and rapid inland penetration of the tsunami: 12.5 min and 15–20 min to reach the school sites. These results depend on the school location, relative to the coastline and the shelter, and the topography (see **Figure 1A**). For instance, MB and G schools in Valparaíso are similarly close to the 30 m elevation contour (around 800 m, which facilitates rapid access to safe high ground), but MB trajectories face a steeper topography on the last section (up to 20%), and it is also closer to the coastline, which means that it can be reached earlier by the tsunami. In contrast, MA and RC schools (especially the latter) ought to traverse long distances (roughly 1,000 and 600 m, respectively) without any significant elevation gain. During these sections of their trajectories, their elevations remain below 10 m.a.s.l. which is approximately the altitude reached by the maximum tsunami penetration (inundation line) in the study area in Viña del Mar (in the case of Valparaíso, this value reaches 8,9 m). It is interesting that RC fares worse than MA despite being nearly at half the distance from its shelter than the latter. This indicates that other elements might be in play for an adequate response, for instance RC's evacuation trajectories include a segment parallel to the coastline (i.e. not moving away from the tsunami attack).

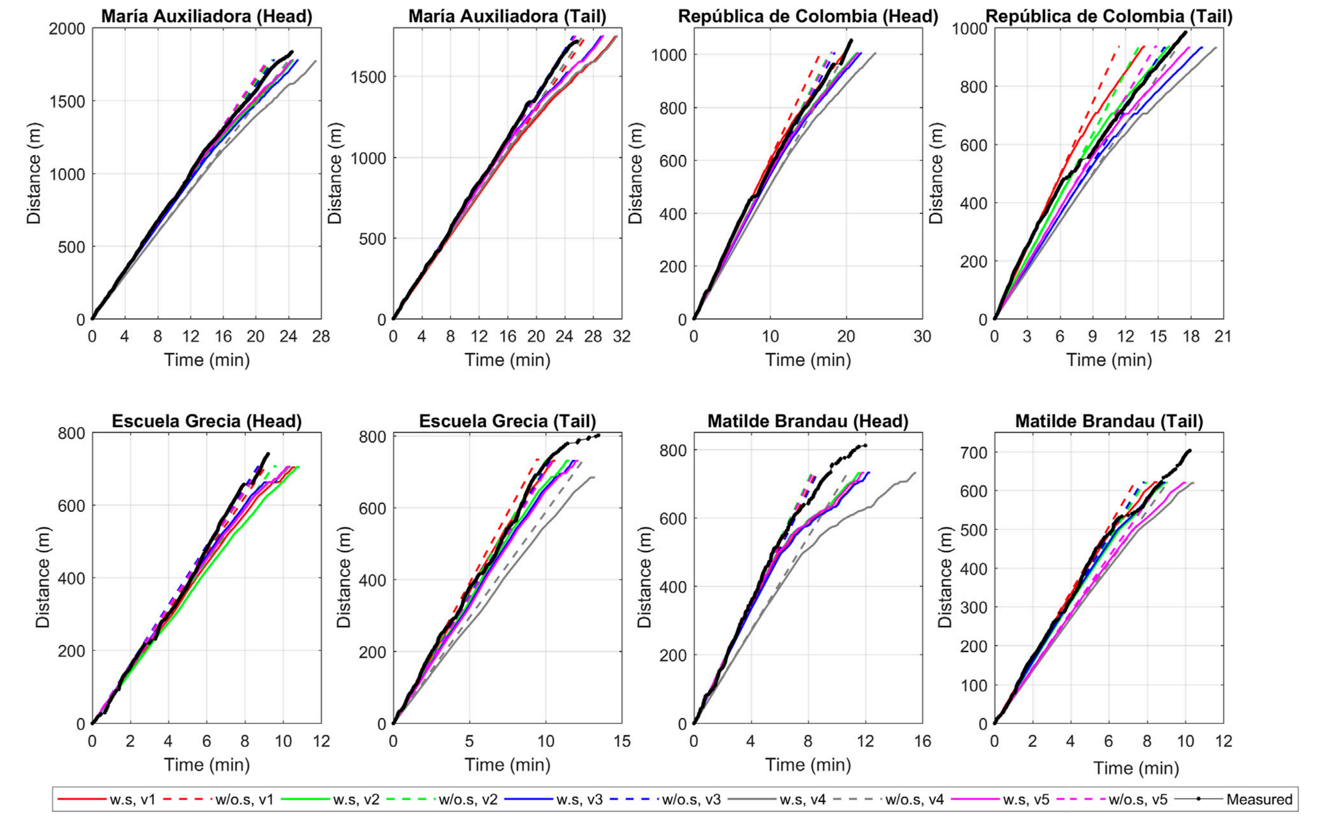

FIGURE 4 | Comparison between the surveyed and modelled evacuation speeds of the four examined schools.

As shown by **Figure 7** and **Figure 8**, the steep topography in the last sections of the evacuation routes (see **Figure 2**) has disparate impacts across the examined schools (although noticeably limited). If the influence of the terrain slope on evacuation speeds is considered in the model, largest changes are as follows. G school (head route, EOT = 16 min) increases its average percentage of affected pupils from 50 to 60%, approximately. MB school (tail route, EOT = 11 min) grows from roughly 2–5%. MA school (tail route, EOT = 9 min) augments from around 5–8%. Lastly, RC school (tail route, EOT = 8 min) increases from 20 to 27%, approximately.

DISCUSSION

Experiences collected from the 2011 Great East Japan Earthquake and Tsunami show the critical importance of proper tsunami evacuation protocols and training, especially for schools and their vulnerable pupils. This example is particularly significant for Chile, as the lag times between the earthquake and the arrival of the tsunami during that event (roughly 30–60 min, see for instance Hayashi et al. (2011)) were significantly larger than those commonly recorded in the South American country. In this respect, the 'Kamaishi Miracle' and the Okawa elementary school (Ishinomaki City) provide contrasting examples. In the former, about 3,000 elementary and junior high school pupils successfully evacuated following the disaster prevention education previously given (including frequent drills) and taking last-minute decisions based on their own judgment (Katada and Kanai, 2016). In the latter, 74 of 78 pupils, and 10 out of 11 teachers, died in the tsunami, despite being the school located right next to a high hill that could had served as shelter. As Hiroyuki (2016) points out, the Okawa school did not have a proper updated plan to deal with this threat, even though the Board of Education of Ishinomaki City had asked schools to prepare one. Moreover, the lack of preparedness led to indecision and stagnation by the school's authorities (Lloyd Parry, 2017). As a result, children and teachers waited for more than 50 min in the playground until the tsunami arrived.

Sixteen primary and secondary schools in Valparaíso and 43 in Viña del Mar are in tsunami-exposed areas. As requested by the Chilean Board of Education, all of them have established emergency response protocols for tsunamis and undergo periodic evacuation training as part of regional-level evacuation exercises enacted by ONEMI. Our analysis (combining fieldwork data and computer-based modelling) for four case studies shows that, despite these frequently practiced drill procedures, safe evacuation might not be fully achievable for a significant number of these schools' pupils in case of a large near-field tsunami, if short EOTs cannot be achieved. In this respect, the 2019 drill-surveyed average pedestrian evacuation speeds for the case studies (from 0.92 to 1.49 m/s) are in line, for

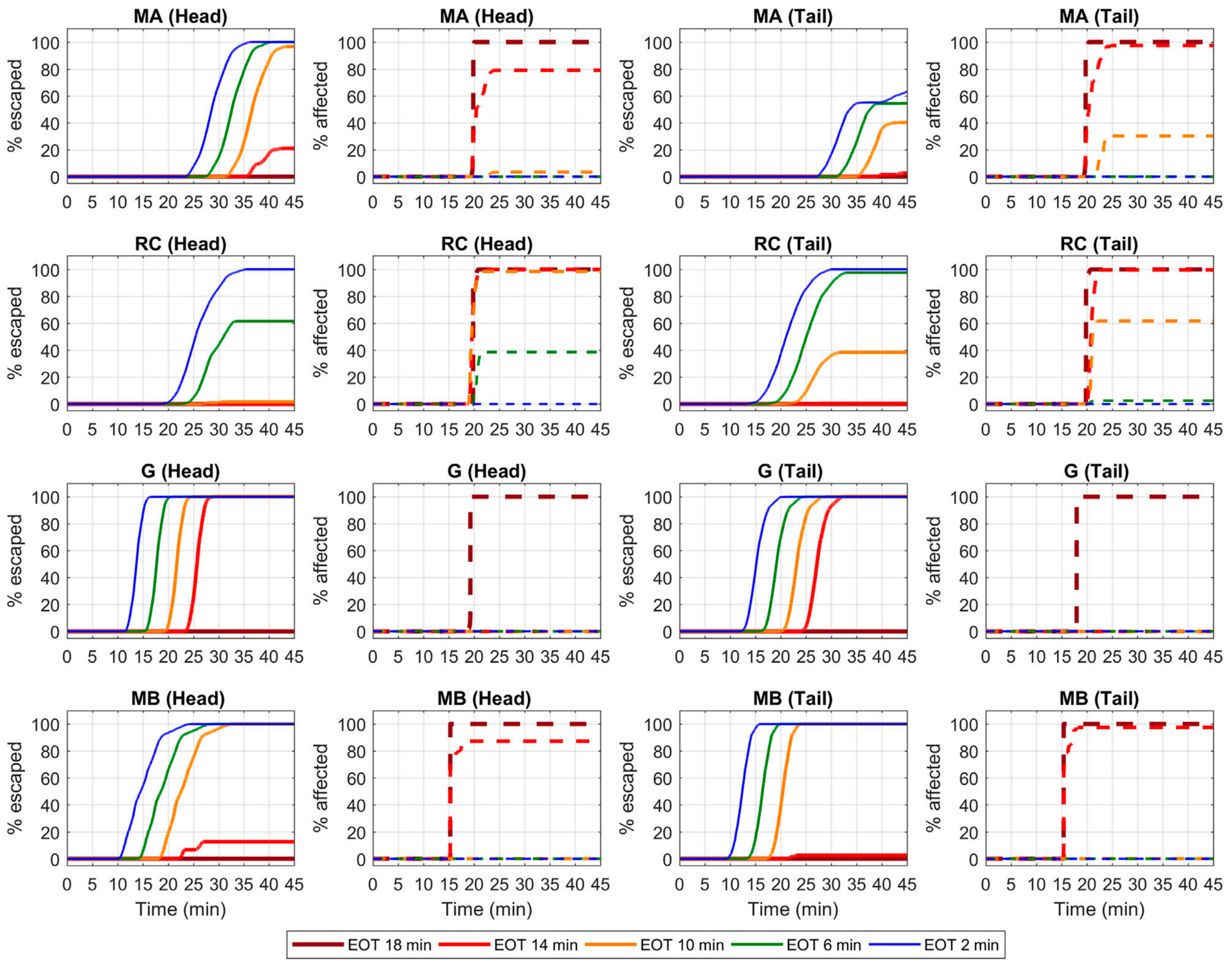

FIGURE 5 | Evacuation curves of the four examined schools (EOT = 2, 6, 10, 14, and 18 min.

instance, with the results reported by Buchmüller and Weidmann (2006) and by (Yosritzal Putra et al., 2020), suggesting a normal performance. Moreover, the data also shows that the pupils behaved according to practiced protocols, rapidly leaving their school buildings, and following the shortest paths to the designated shelters. However, they did not always arrive at them, as shown by the routes of the Grecia and the República de Colombia schools in **Figure 1C** and **Figure 1E**, respectively.

Despite these overall appropriate evacuation behaviours, long distances to safe locations (up to roughly 1,840 m) combine with steep terrain slopes (see **Figure 2**) that could diminish evacuation speeds, and with short tsunami-arrival times, to make full evacuation unlikely in the case of a catastrophic tsunami event. This dangerous situation could occur if the schools' evacuation onset times (which include previous indoor evacuation) exceed threshold values between 3 and 14 min. These short windows impose severe restrictions for an evacuation. On the other hand, our results show that the terrain slope, frequently included on tsunami evacuation modelling (Sahal et al., 2013; Schmidtlein and Wood, 2015; Solís and Gazmuri, 2017) might have a limited impact on pedestrian speeds and therefore on the number of affected evacuees in our case studies. A reason for this could be that, while Tobler's classic hiking function (Tobler, 1993) predicts significant speed reduction as slope increases, pedestrians (especially young ones, like the K-12 pupils included in this research) might be able to sustain evacuation speed along steep slopes, if these segments do not extend excessively. In our case studies, route sections with terrain slope above 3° do not last for more than 600 m, approximately (see **Figure 2**). In this respect, we note that (Yosritzal Putra et al., 2020) found out that during short walking distances (190–515 m) in a tsunami evacuation drill in Padang, Indonesia, children walked at faster speeds compared to adults in a long-distance.

Existing and frequently-practiced evacuation protocols are based on reasonable nation-level criteria: aiming at reaching an open public space with an elevation of at least 30 m, out of the floodable area, using the shortest possible route, which are enforced by municipal emergency offices following ONEMI's guidelines. Moreover, as shown by the 2019 drill report (ONEMI, 2019), the coastal municipalities of the Valparaíso

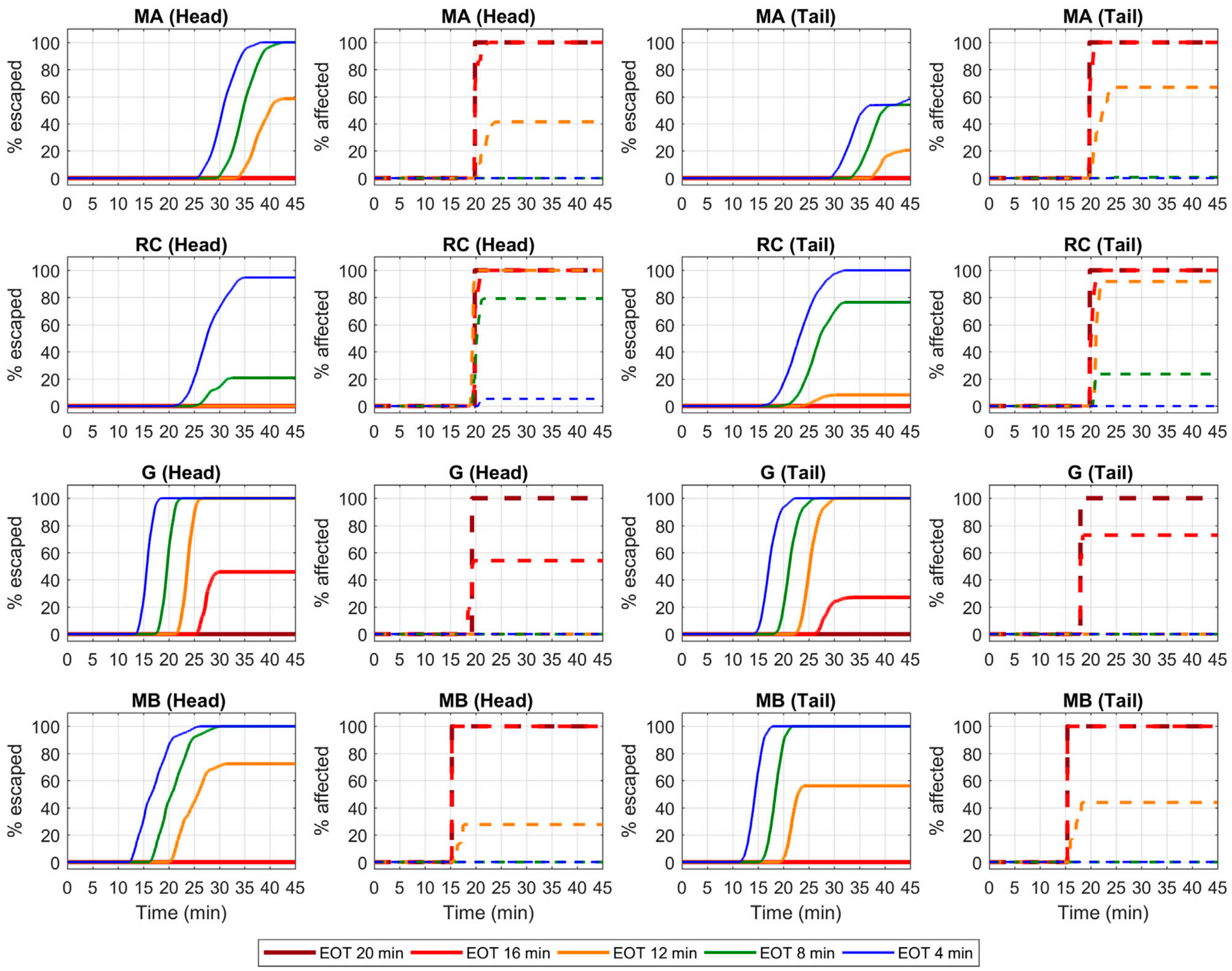

FIGURE 6 | Evacuation curves of the four examined schools (EOT = 4, 8, 12, 16, and 20 min.

region have disparate accomplishments of these guidelines (e.g., six of 21 municipal emergency plans had not been updated when the drill was held), which highlights the importance of a nation-level guidance for disaster risk reduction. However, as demonstrated by our results, this top-down approach might not be sufficient to adequately cope with a worst-case scenario in cities like Valparaíso and Viña del Mar, given the demanding on-site conditions as those underlined above. Hence, we suggest complementing existing national-level protocols with a more detailed, case-by-case and bottom-up approach, comprising at least two further lines of development. First, recent advances in tsunami hazard microzoning (Zamora et al., 2021) allow to examine the tsunami threat as the outcome of multiple stochastic earthquake scenarios, leading to a qualitative, spatially-detailed, hybrid characterization of the hazard through the combination of resulting flow depths and arrival times. This type of microzoning could allow the development of more detailed evacuation strategies for each school, aiming at finding the least hazardous routes (Zamora et al., 2021) instead of the shortest ones. Moreover, probabilistic tsunami modelling allows better grasping of non-linear effects such as refraction, which would impact on the extension and duration of the inundation.

Second, the ongoing approach to evacuation planning could also be enriched with improvements based on the judgment of the staff of the schools (collected, for instance, after a drill), or inputs provided by the community, real-world experts and academia, with the final aim of fostering active and practical decision-making during an emergency (Oka et al., 2020). As shown by Nakano et al. (2020), consensus-making between disaster experts and non-experts can lead to establishing improved and proactive preparedness activities by non-expert teachers. Moreover, evacuation models like the one included in this paper could help schools to critically examine current evacuation scenarios and related information (e.g., evacuation maps) to support enhanced responses in a disaster. In line with this, autonomous actions to deal with last-minute changes (e.g., blocked roads due to the tsunamigenic earthquake or a remarkably rapid arriving tsunami) are not currently prepared

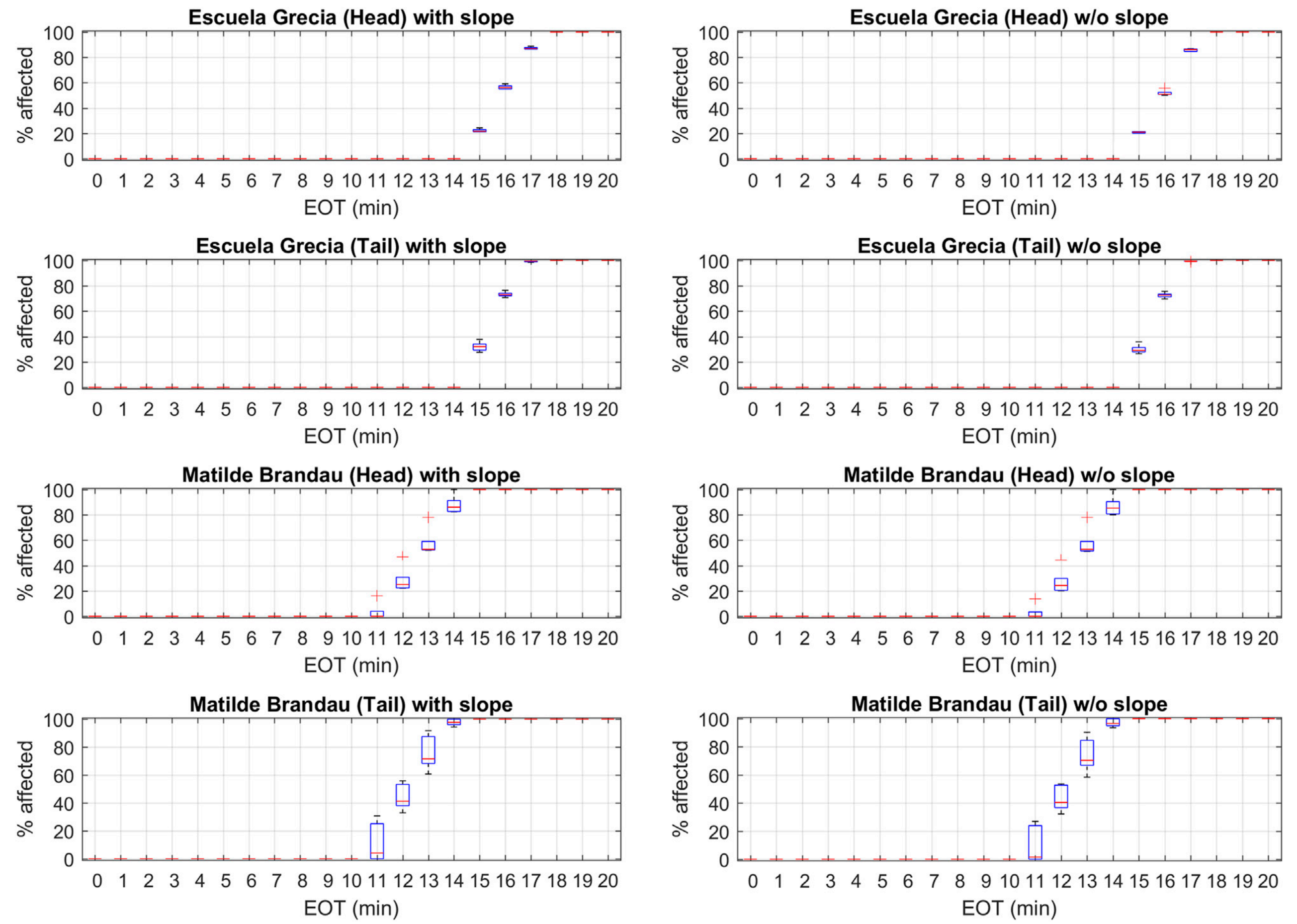

FIGURE 7 | Box plots showing the percentage of affected evacuees of the G and MB schools in Valparaíso, for evacuation speeds v1 to v5.

in the examined area. For instance, most schools in the floodable areas are close to suitable high-rise buildings that could serve as tsunami vertical-evacuation refuges, therefore significantly shortening evacuation times. Nevertheless, ONEMI recommends vertical evacuation only as a second alternative only if horizontal escape is not feasible (ONEMI, 2014b).

Following these lines of development, the evacuation potential of each school could be assessed and improved in the light of its particularities, for a range of disaster scenarios, under the guidance of local municipal emergency officers. These singularities might include geomorphological features (e.g., location, expected tsunami arrival time and flow depth, condition of the evacuation routes and/or shelter) and the characteristics of pupils and staff. However, this approach could imply significant difficulties for local emergency officers and the non-expert teachers and staff of schools, due to a lack of scientific knowledge or updated data. These difficulties could be mitigated, for instance, with recent efforts (Newton, 2012; Wood et al., 2017) to develop online user-friendly simulation platforms, where diverse types of users could build disaster scenarios and also test different evacuation responses to them. These results, in turn, could be used for both management, educational and training purposes.

Lastly, we underline that there are significant opportunities for increasing the use of tsunami evacuation drills in Chile as sources of data for scientific research, ultimately leading to better evacuation planning and emergency management policies. Currently, during every drill ONEMI coordinates hundreds of volunteers that act as examiners of the activity, having to complete an assessment checklist focused on both the evacuees' performance and the characteristics of the evacuation routes. However, more accurate data is not typically surveyed, nor are information technologies included in these analyses. In line with these, protocols for gathering and assessing information, like the one introduced in this work, complemented with other technologies like drone imagery and automatic processing of videos from traffic cameras, could be also enforced by ONEMI. This gathered data could be used, for instance, for the validation of evacuation models for enhancing future evacuation planning (see for instance Solís and Gazmuri (2017)). In line with this, while the focus of this study was on K-12 students, we suggest that our approach is also helpful to examine other emergency scenarios and populations. These include (for instance) night-time evacuation drills for the general population (as the one conducted by ONEMI in the northern coast of Chile in 2012), which aim to train and examine the inhabitants' response during other times apart from

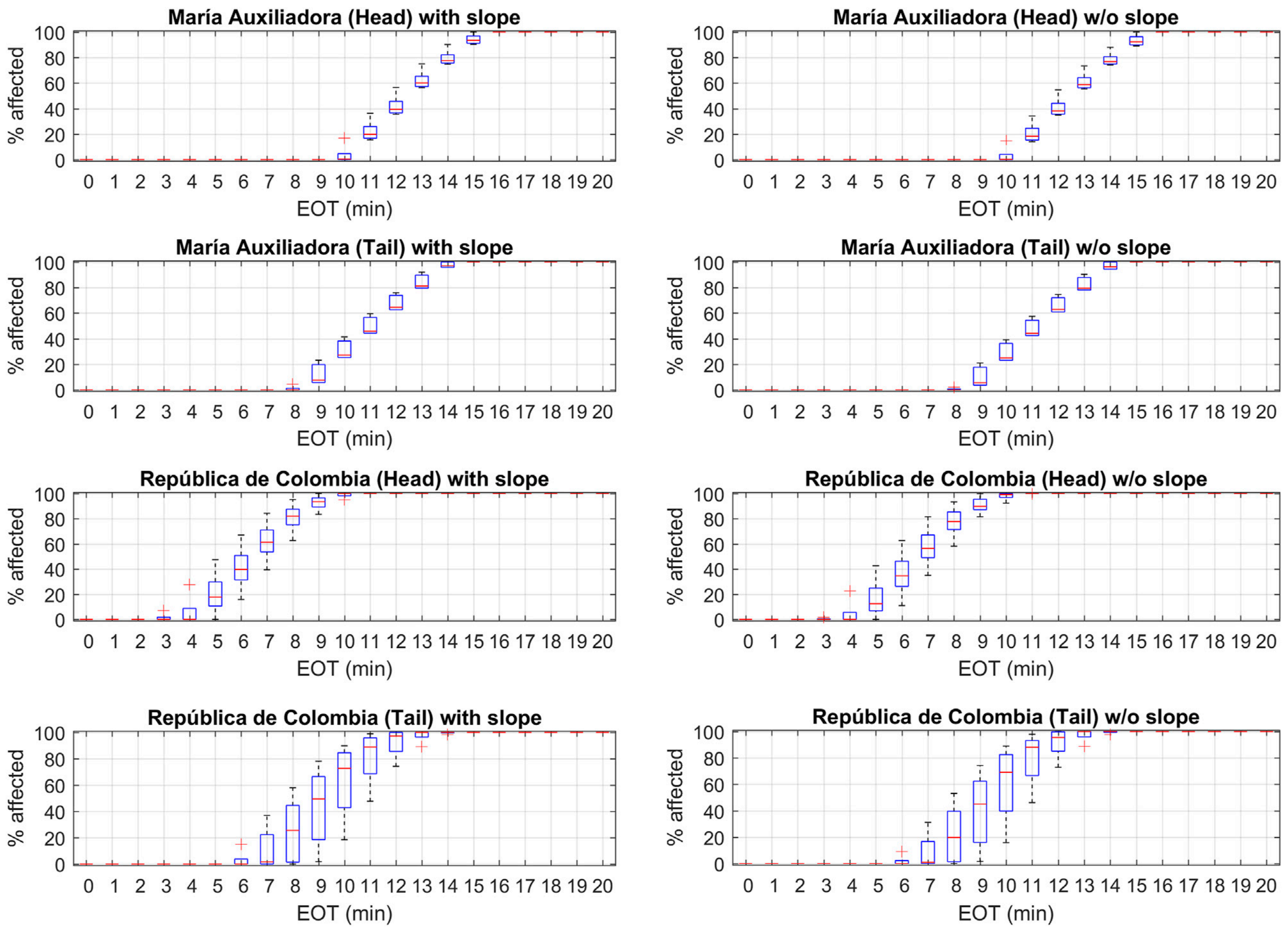

FIGURE 8 | Box plots showing the percentage of affected evacuees of the MA and RC schools in Viña del Mar, for evacuation speeds v1 to v5.

working hours. By expanding the scope of our analysis, through its integration with state-of-the-art seismic and tsunami modelling practices, and the public discussion of its findings, we would be able to deliver a critical assessment of existing tsunami risk policies at a general level in Chile and, more important, to contribute to fostering a 'ready-to-act' condition across the population.

CONCLUSION

This paper analysed the evacuation performances of four schools in Valparaíso and Viña del Mar, Chile, coupled with tsunami flood modelling. Our findings allow us to deliver several conclusions that could contribute to tsunami evacuation planning and further research.

- We engaged with four primary and secondary schools in Valparaíso and Viña del Mar and developed a methodology to survey their evacuation performances during a tsunami evacuation drill held on September 5, 2019.
- We demonstrated that our previously developed agent-based model could accurately grasp the drill performance of the evacuees. Therefore, we used it to assess this performance coupled with a worst-case historic tsunami scenario (based on historical data from the 1730 event), using the four schools as case studies.
- Our results for these four case studies show that following nation-level evacuation strategies (frequently trained on drills) might lead to significant human losses across these schools (up to 100% of their pupils) if rapid Evacuation Onset Times (EOT) cannot be enacted.
- Currently, these evacuation strategies are not based on precise tsunami flood modelling, nor do they grasp the characteristics of each school (relative to pupils, staff, and geomorphological conditions).
- User-friendly tools need to be developed to allow each school community to build and assess disaster scenarios, leading to better disaster education and improved responses in an earthquake and tsunami emergency.
- Tsunami evacuation drills in Chile offer significant research opportunities, which have not (hitherto) been fully addressed by current emergency management authorities. Updated protocols for gathering and assessing information during drills, supported by information technologies, could

lead to enhanced and validated models for better evacuation planning.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The study was conceived and developed by all authors, who also directed the field survey AG carried out the tsunami and evacuation modelling JL prepared the first version of the manuscript with reviews by PAC and AG All authors contributed to editing the final version of the article.

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On Epistemic Dissonance: Contesting the Transdisciplinary Disaster Risk Reduction Education, Research, and Practices

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INTRODUCTION

Over the last century, the ever-present challenges facing disaster risk reduction (DRR) have driven several paradigmatic shifts in disaster risk research, lacking adequate bridging between research focused on a biophysical understanding of natural hazard mechanisms, and research focused on societal root causes of disasters. Over the last two decades, a transdisciplinary approach to research and practices has been widely advocated as an appropriate mode of acknowledging and reconciling multiple feedbacks between societal developments, Earth's dynamics, and resulting disasters (e.g., Lang et al., 2012; Matsuura and Razak, 2019; Bendito, 2020).

To list just a few of these efforts, "Transdisciplinary Education for Disaster Risk Reduction" was an official side event at the UN World Conference on Disaster Risk Reduction in Sendai in 2015, and the largest European funding scheme, Horizon 2020, launched a call in 2018 for "Large-scale demonstrators on nature-based solutions for hydro-meteorological risk reduction", that should be transdisciplinary, among other attributes. Most recently, the Organization for Economic Co-operation and Development has approved a report on addressing societal challenges using transdisciplinary research, largely motivated by another current disaster—the Covid-19 pandemic (OECD, 2020).

These efforts have been supported by conceptual developments in transdisciplinarity. Aside from its frequent use as a vague alternative for other disciplinary entanglements, such as inter- and multi-disciplinarity, transdisciplinarity *sensu stricto* denotes an approach in which two or more disciplines collaborate on the basis of generalised axiomatics, thus calling for a generalised epistemology (Jantsch, 1972). In recent developments, the term has also increasingly gained a connotation for involving local communities of non-academics in knowledge production (Rigolot, 2020), thus mobilizing various knowledge systems in order to gain credibility and legitimacy (Cash et al., 2003). This challenges the essential gap that is created by boundaries being constantly delineated between the scientific approaches, and the civic epistemologies of the communities and decision-makers. Using the 2012 L'Aquila earthquake, Donovan and Oppenheimer (2016) have shown, for example, how the neglect of social approaches resulted in a limited framing of the scientific advice in DRR. It has been argued that the transdisciplinary approach is suitable for "*. . .problems that are complex and multidimensional, particularly problems (. . .) that involve an interface of human and natural systems* . . . " (Wickson et al., 2006). Indeed, DRR research and practice fulfils all these challenges.

Importantly, the above-mentioned efforts to achieve transdisciplinary approaches have gradually contributed to reducing epistemic injustice, which denotes the dominance of certain scientific approaches or groups of people based on distorting others' capacity to understand and know the world (Grasswick, 2017). Currently, the DRR community can hardly complain of a global scarcity of publication platforms in which to present their research, regardless of its scope and approach.

Nonetheless, a critical assessment would reveal that these platforms often serve as occasional crossroads on independent thematic avenues pursued by researchers. In disaster risk management (DRM) practices, on the other hand, an increasing number of developmental projects have been launched, consisting of experts from various disciplines. Yet again, the proclaimed transdisciplinarity often proves to be an illusion, as current organisations and funding vehicles continue to evince reluctance to fund and perform transdisciplinary research and practice (McLeish and Strang, 2016). Notably, Malamud and Petley (2009) pointed out that some geoscientists perceive a lack of evidence supporting the efficacy of approaches employed by social scientists in DRR. This urges a fair and self-critical evaluation of how we conduct and assess our work as a DRR community. In the following lines, I argue that at least some of these shortfalls in research and practice can be explained by what I call epistemic dissonance, a term derived from theories of epistemic injustice and cognitive dissonance.

EPISTEMIC DISSONANCE: CONCEPT AND NARRATIVES

Epistemic dissonance refers to cognitive and behavioural inconveniences resulting from situations in which scientists and practitioners are expected to accept and act upon information obtained by untrusted epistemologies. The basis for such epistemological clashes lies in differential perceptions of uncertainties peculiar to each discipline involved. I will illustrate below some representative perceptions of uncertainties with examples from historical research in DRR, with the presumption that such studies clearly accept the need for axiomatics based both in natural sciences (e.g., seismology, geomorphology, and hydrology), and social sciences and humanities (e.g., memory studies, cultural history, historical sociology). However selective the use of historical disaster research as an example might be, it is also supported by its critical contribution to central concepts revolving around DRR, such as traditional ecological knowledge, adaptation, and resilience. For the following reasoning, I will unconventionally, and perhaps quite impertinently, use examples from anonymous reviews of studies published in a couple of first-tier journals that present themselves as open to the perspectives of various disciplines, and that pursue sustainable developmental goals (indicating at least some notion of transdisciplinarity)[1].

Historical disaster research has diverged into at least two main directions devoted to 1) building parameterised historical catalogues and time series of natural hazards and disaster events, along with their social impacts, and 2) reconstructing single- or multi-case historical events in terms of their roots, impacts, and societal adaptive mechanisms (e.g., Schenk, 2007; Raška et al., 2014; Adamson et al., 2018). Notably, it is the first direction which builds on relatively weaker interdisciplinary collaborations that generally receive widespread acceptance across the DRR community, and become used for evidence-based policymaking. This is despite parametrised catalogues and time series of historical events all essentially require selection and generalisation of data for the sake of quantitative consistency, while partly neglecting contextual information about past and current discourses framing the original purpose, and present-day understanding of these data. My personal experience from discussions with historians is that these simplifications would be considered by many to be major flaws in the research. Neglecting the notion that geoscience terms and approaches employed in DRR are no more than one cultural and renegotiable representation of the world we live in (Palsson et al., 2013) may result in significant simplifications. Typically, these involve approaches where the data are collected from local communities and classified according to pre-established categories complying with researchers' experience and selected analytic methods. Such approaches pose a major barrier to the practical goals of DRR, because they neglect ways in which the world is experienced and evidenced by communities themselves, and therefore limit the acceptance and effectiveness of DRR interventions. Such a notion fundamentally calls for socialising the materiality of natural hazards. This claim can be reflected by searching for new ways of sensing and evidencing natural hazards and their impacts, while reconfiguring relations between researchers and local communities (e.g., Klimeš et al., 2019).

Perhaps even stronger reluctance to reconcile different perspectives can be seen in examples from the second branch of historical disaster research. First, there is the broadly accepted view that some kind of reality exists independently of our perception. As one reviewer claimed: "*when studying historical sources* (. . .) *it is always difficult to separate clearly the "facts" from the "interpretations"*." This distinction is drawn from principles maintained and secured in many science disciplines, stating that first we observe and collect facts, which are only then subject to interpretations. In historical research, the facts are, however, construed either by the writer (e.g. the chronicler and his funder) and by the historian approaching the data. Any enquiry is therefore situational. This does not negate the claim that historical methods are "*governed by inter-subjectively acceptable rules of inquiry*" (Iggers 1975: p. 5). Whether "*. . .there is always the possibility that we use the historical findings that match our "mental model*"", as another reviewer noted, is not a question aimed specifically at historians. For how different is this questioning from that which can be addressed to other scientists who are 'forced' to accept a selection based on recently formulated research problems, accepted theories, and their personal research experience (e.g., when segmenting terrain into landforms, choosing a location for geophysical profiling, or interpreting cause and effect of Earth's dynamics).

[1]Since all papers, for which I received the cited reviews, have been published, this exercise is by no means to criticize editorial policy. I am also aware that critical comments raised by reviewers may have been based on actual flaws in the reviewed papers. For this reason, I did my best to select and comment only on examples that point to institutionalized cross-discipline differences in perspective regarding uncertainties in data and interpretations. Also, I admit that the evidence is one-sided as it comes mainly from historical disaster research submitted to what may be called nature-based science journals.

Even after accepting the historical approaches, some would argue that "*it is interesting to see how pieces of information have been put together, but the final advancement is limited* ... ". Although historical cases are always contextual and reflective, historians attempt to draw more general causal inferences from their research. While the predictive efficacy of such inferences may remain low, historical enquiry often provides explanatory conceptualisations that go beyond the knowledge of contingent relations observed in large-replication studies. The last objection is perhaps most peculiar among the different ways of coping with uncertainties across disciplines. It was simply stated with the question of one reviewer, "*Why are the authors giving approximate measurements?*". Explicitly acknowledged approximate measurements are simply historiographical appreciation of the uncertainties inherent in statistical measures applied in other disciplines. Such statistical calculations are not always possible with documentary data, since data triangulation and quantitative assessments are hindered by frequent paraphrasing and contextually differential meanings of similar statements (in text or figures). The particular ways of evidencing and presenting the uncertainties manifest themselves as yet another attribute of different epistemologies and thus as possible roots of epistemic dissonance. Contradictory to the above apology of historical research, we should also admit that historians may sometimes be too keen to address criticism by exacerbating the constructivist stance regarding the nature of the data and relativism in their interpretation (Tosh, 2006 for discussion). Mirroring the above in claim for geoscience research, we may assert that bringing the disciplines into a viable dialogue would necessitate materialising what the humanities consider purely social, thereby accepting that much of the social is conditioned by material worlds (Clark and Yusoff, 2017) and, in turn, produces new materiality.

DISCUSSION: A WAY FORWARD

The epistemic dissonance briefly illustrated in the previous section is strikingly persistent in disciplines due to cognitive lock-ins. Among researchers pursuing extended careers in their fields of expertise, disruptive thinking, allowing a breach of such a lock-in is only occasionally adopted in later career stages. This holds also for a large part of the DRR community, which, on the one hand, pursues multi-faceted problem-oriented research, but does so by bringing together researchers recruited from different fields of expertise, as diverse as geomorphology and psychology. Helpful methodological apparatus and examples are at hand, however. They range from science-based critical realist perspectives in social studies and humanities, critical physical geography (Lane, 2017) and STEAM approach (Ludlow and Travis, 2019), toward intervention-aimed Participatory Action Research (Meyer et al., 2020), all enabling the crossing of the ontological nature-human divide, and their respective epistemic perspectives. What is needed? Revisiting the above referred transdisciplinary education for disaster risk reduction event, I argue that we should go beyond illustrating good practices in local partnerships between universities and communities. Members of the DRR community face no lesser challenge than to take responsibility for promoting multi-epistemic education from the lowest levels of education within and outside of DRR programmes. This may require stepping outside of comfort zones since it has been shown in educational research that personal epistemology (or epistemic beliefs) of teachers is formative of the teaching approaches and of the expected teaching outcomes (Lunn et al., 2015). More variegated teaching outcomes could be supported by focusing on the learning processes instead of its goals (Bang and Medin, 2010), by joint teaching programmes, and by place-based learning—however mediated by cultural diversity of teachers and students. Fostering understandings and justifications for diverse epistemic perspectives would, in turn, enable students and practitioners to develop axiomatics that may enhance effectiveness of the integrative disaster risk reduction and management.

AUTHOR CONTRIBUTIONS

PR is sole author of this paper, being responsible for design and writing of the contribution.

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An Agent-Based Approach to Integrate Human Dynamics Into Disaster Risk Management

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Disaster risk management (DRM) is the application of disaster risk reduction policies and strategies to reduce existing disaster risk and manage residual risk. However, due to dynamic human factors, it is challenging to depict and assess the effectiveness of DRM measures, and their implementation usually lacks a sufficient evidence-based evaluation process. Therefore, this study developed an agent-based model to integrate dynamic human behaviors into the DRM measures and evaluated their effectiveness in casualty reduction. The model was calibrated to simulate the debris flow event at Longchi town, China in 13 August 2010. The early warning system (EWS) and related DRM measures were taken as examples. The effectiveness of different DRM measures was quantitated by comparing the number of potential casualties. The main findings were: 1) EWS was very effective for community-based DRM as it could significantly decrease the average casualties by 30%. 2) Credibility of EWS was critical to its effectiveness. Less credible EWS might reduce its effectiveness by 9%. 3) EWS could be supplemented by other measures to further reduce casualties by 6%. 4) The downside effects of other DRM measures to EWS might exist and reduce its effectiveness by up to 5%. This study put forward an evidence-based approach to help policymakers select more cost-effective DRM measure, especially in the less developed countries where the available resources for DRM are limited.

Keywords: disaster risk management, early warning system, agent-based modeling, human dynamics, debris flows

INTRODUCTION

Disasters can bring devastating loss of life and injuries as well as damages to critical lifelines and infrastructures. Nowadays, disasters are more threatening than we ever expected to the social, environmental, and economic components of sustainable development, and subsequently, there is an increasing demand for taking ambitious actions to disaster risk management (DRM). Communities in mountainous areas are prone to natural hazards due to the complex geological settings that foster favorable conditions to mountain hazards (Cui et al., 2021). Governments are liable to ensure the safety of residents, critical lifelines, and infrastructure. DRM measures have been employed to alleviate the extent of suffering and hardships caused by hazards. However, due to the variety of community settings regarding residents and facilities, DRM measures would not effectively reduce disaster risks without considering these factors. Instead, when implemented to the community level, the DRM needs to precisely tailor its measures for the locals, including the environmental and social conditions of communities and individual differences of their residents.

Take the early warning system (EWS) as an example. As one of the essential DRM measures, EWS is widely utilized in many cases worldwide to provide the lead time for residents to evacuate from disasters (Alcántara-Ayala and Garnica, 2013). The United Nations Office for Disaster Risk Reduction (UNDRR) defined EWS as "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and insufficient time to reduce the possibility of harm or loss" (UNISDR, 2009, p5). Smith (1996) divided the EW process into three inter-related stages: evaluation/forecasting, warning/dissemination, and response. Each stage involves many natural and human aspects that can affect the effectiveness of the EWS. At the community level, its effectiveness is primarily associated with the number of casualties prevented. To improve the effectiveness of EWS, many of current studies focused on natural science and utilized new technologies and scientific advances to improve its accuracy and timeliness, such as geological knowledge and risk scenarios (Intrieri et al., 2012), UAV (unmanned aerial vehicle) and InSAR (Interferometric Synthetic Aperture Radar) (Mantovani et al., 2016; Peppa et al., 2016; Mateos et al., 2017) and rarely considered the influence of human behaviors. As human is also an essential factor constraining the effectiveness of EWS (Twigg, 2003; Intrieri et al., 2012), it is necessary to consider the individual differences in community vulnerability in order to achieve more scientific and efficient DRM.

Human are complex creatures, and the behaviors of each person vary objectively and subjectively. In the context of disasters, their characteristics, such as gender (Bateman and Edwards, 2002), risk perception and awareness (Baker, 1991; Gissing et al., 2008; Smith and McCarty, 2009), social and physical conditions (Baker, 1991; Şahin et al., 2019), experience and knowledge (Nakanishi et al., 2019), can result in various emergency behaviors during disasters events and affect the effectiveness of EWS. These dynamics of human factors make it challenging to simulate and assess the effectiveness of EWS; thus, many models were neglected with an absence of incorporating human dynamic decision-making process (Schwarz and Ernst, 2009; Groeneveld et al., 2017). As a primary tool for modeling individual decision-making and complex interactions (Matthews et al., 2007), the agent-based modeling (ABM) approach offers a quantitative, theoretical, and mechanistic approach to explain and predict the typical findings in disaster risk research, especially when humans are involved during the DRM process.

Therefore, to extend the traditional disaster risk model, this study adopted the ABM approach to relating DRM measures and human behaviors during disaster events. The objectives of this paper include: 1) development of a model to simulate human behaviors and visualize their interactions with each other and the environment during disasters; 2) assessment of the effectiveness and influential factors of EWS and related DRM measures in casualty reduction and 3) provision of scientific-based evidence for better prioritization during DRM and resilience building in disaster-prone areas by examining the effectiveness of DRM measures.

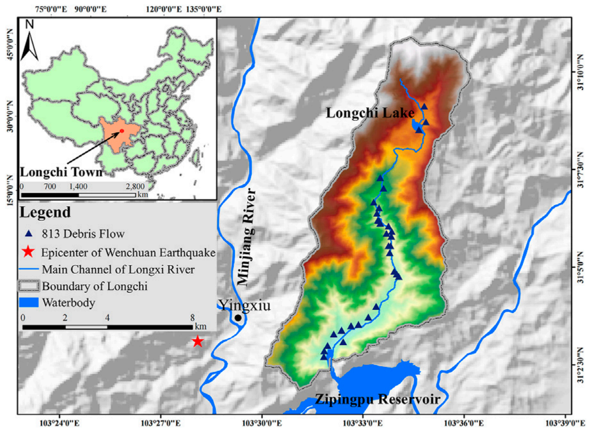

FIGURE 1 | Location of Longchi town.

STUDY AREA

Longchi town (31°N, 103°E), Sichuan Province, is located in the southwest of China (**Figure 1**), approximately 80 km to the northwest of Chengdu. In the 2008 Wenchuan Earthquake, as it neighbored the epicenter (Yingxiu) with a straight-line distance of 3 km, Longchi was hit with 36 people dead, 17 missing, and 1,558 injured.

Afterward, due to post-earthquake fractured rock and loose soil on steep slopes, Longchi repeatedly suffered mass movement processes (Zhang et al., 2019). The debris flow that occurred on August 13th, 2010 (the 813 debris flow) was one of the most destructive debris flows. The 813 debris flow was a flash flood-debris flow disaster chain, and through more than 50 gullies simultaneously occurred debris flows with a total volume of 7.78 × 106 m^3 (Xu et al., 2012). This event caused 495 casualties (about 3,000 population in total) and substantial economic losses. Almost all the houses and roads near the river and the gullies were destroyed.

METHOD AND DATA

The ABM (Agent-based modeling) approach is a modeling method in which individuals (e.g., people, animals, and cells) and their interaction with each other and their environment are explicitly represented. It includes conceptions from mathematics, physics, biology, sociology, and other disciplines. One feature of the complex system theory was

TABLE 1 | Agents and attributes.

Agents	Attributes	Data source
1. Resident	Physical: age, gender, vision, stamina, safety Mental: risk perception, disaster experience, knowledge level	Physical data from National Bureau of Statistics of China (2011); Mental related from the interview
2. Disaster	Rainfall, locations of gullies	Rainfall station and Xu et al. (2012)
3. House	Location, state (safe or flooded)	Location from Satellite Image
4. Disaster shelter	Location, number of residents arrived at shelters	Location from field investigation

that the global phenomenon came from the macroscopic emergence of micro-interactions (Green and Sadedin, 2005). In disaster event modeling, the challenging task was to predict people's behaviors from many factors affecting human decisions. Studies in disaster risk management using ABM gained traction and showed that it was possible to integrate scientific theories on human behavior and perception into disaster risk reduction. (Haer et al., 2016a; Haer et al., 2016b; Jenkins et al., 2017; Aerts et al., 2018). The ABM could simulate individual behavior, where agents acted in their interests with decision rules for different adaptation actions (Aerts et al., 2018). The current study adopted the ABM method to consider human risk perception and dynamic behaviors during the 813 debris flow disaster events and generate the potential casualty. The changes in casualties were used to reflect the effectiveness of the EWS and related DRM measures.

Model Components

This study developed the ABM model with two types of components, model environment, and agent. The model environment created the foundation for the agents to move and interact. In this case, the environment was reconstructed based on the physical and social conditions of the 813 debris flow event. There are four types of agents in this model, i.e., disaster, resident, house, shelter. Each type of agent was assigned with its own attributes that would formulate the agents' behaviors rules.

Model Environment

This model used GIS and RS data, including topography, the river system, village, and building locations to depict Longchi town before the 813 debris flow. The digital elevation model (DEM) of Longchi, at a resolution of 5 m × 5 m, was imported to the ABM modeling platform from ArcGIS. Debris flow volumes during this event were calculated based on the precipitation records.

Agent and Their Attributes

This ABM model included four types of agents: residents, disasters (debris flow), houses, and disaster shelters, among which residents and disasters agents could move and interact with others. Each agent possessed different attributes to simulate the disaster event by encapsulating the psychology, sociology, geography, and disaster movement mechanism. As shown in **Table 1**, each type of agent was characterized by several attributes.

TABLE 2 | Evacuation willingness and evacuation strategy probability: The probability of starting evacuation.

		Risk perception		
		Low (%)	**Medium (%)**	**High (%)**
Knowledge level	Low	50	56	44
	Medium	55	62	49
	High	65	73	58

Agent Behaviors Design

Behavior rules were fundamental to the ABM model simulation. This study defined the behavior rules based on the data collected through field investigation and semi-structured interviews, which included risk perception, willingness to evacuation, emergency choice, knowledge level on disasters, numbers of disaster trainings attended, conditions of DRM measures.

For the design of the semi-structured interview, we conducted a focus group interview with 13 residents to gain an in-depth understanding of their perception and behaviors on disasters and related DRM measures. The follow-up interviews were then conducted in all villages in Longchi with 54 households to investigate their mental condition and behaviors before and during the 813 debris flow. This survey covered nearly 50% of current resident households, widely distributed in locations, professions, gender, and age. Collected data have been processed in SPSS to discover the general behavioral rules for use in the ABM model.

Resident Agent: To Simulate Human Behaviors During the Disaster Event

Each resident was displayed as an autonomous agent in the system and had physical and mental attributes that could influence his or her behaviors during disaster events. In this model, two factors could affect human behaviors: evacuation willingness (EW) and evacuation strategy (ES). The evacuation willingness determined whether the resident agents started to evacuate. Residents with high evacuation willingness were set to evacuate immediately when they received alerts. In contrast, those with lower willingness would hesitate and start to move when the disaster agent was within a visible distance (40 m). Once the resident agent started to evacuate, evacuation strategies would determine how the resident agent would move. There were two types of evacuation strategies in this model: normal and panic. For normal evacuation strategies, resident agents would move toward disaster shelters or places with higher elevations. Otherwise, they would move in any direction as long as it was away from the disaster agent.

TABLE 3 | Evacuation willingness and evacuation strategy probability: The probability of the normal strategy.

		Knowledge level		
		Low (%)	Medium (%)	High (%)
Trainings	No	65	69	78
	Yes	83	88	100

TABLE 4 | Attributes of resident agents.

Attributes	Categories	Ratio/value
Gender	Male	51%
	Female	49%
Age	0–14 years old	19%
	15–64 years old	63%
	Over 64 years old	18%
Speed (in mountains)	0–14 years old	200–400 m/h
	15–64 years old	600–800 m/h
	Over 64 years old	300–500 m/h
Stamina	0–14 years old	10–20
	15–64 years old	50–55
	Over 64 years old	20–25
Disaster knowledge level	Low	24%
	Medium	48%
	High	28%
Disaster risk perception level	Low	15%
	Medium	35%
	High	50%
Training and drills	Never participated	43%
	Once	17%
	More than once	41%

This study obtained the probabilistic correlation between the attributes of resident agents (knowledge level, risk perception, experience, training) and EW/ES using the cross-tabulation analysis of the interview results in SPSS (Kamakura and Wedel, 1997). Based on the knowledge level and risk perception, each resident agent was assigned a probability to start evacuation (**Table 2**). At the same time, each of the resident agents was set to obtain a probability of conducting a normal or panic strategy (**Table 3**) based on knowledge level and times of training.

Disaster Agent: To Simulate Debris Flow Movement

Disaster agents in this ABM model represented the debris flow disaster, and their attributes included gully locations and debris flow volumes. The disaster agent will move from the upstream of the debris flow gully to the deposition area. The number of disaster agents was calculated based on the debris flow volume calculated for that specific debris flow gully. The gully locations in this model were determined based on the field investigation after the 813 debris flow (Chang et al., 2014).

Data Preparation and Simulation

Resident Data

Each resident was displayed as an autonomous agent in the system and had physical and mental attributes that could influence his or her behaviors during disaster events. These attributes of resident agents (**Table 4**) were derived from the

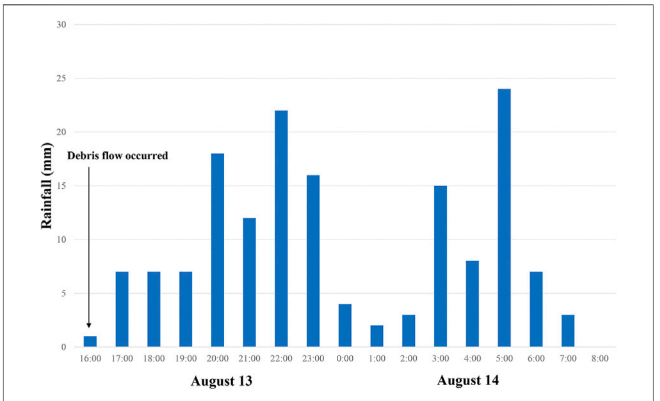

FIGURE 2 | Hourly precipitation in Yingxiu town during the 813 debris flow (Xu et al., 2012).

Sixth National Population Census of the People's Republic of China (National Bureau of Statistics of China, 2011) and the interviews. The data management and analysis were performed by using SPSS. The analysis results formed the physical and mental attributes of each resident agent in the ABM world (**Table 4**).

Disaster Data

Hourly precipitation data from the monitoring station at Yingxiu town (**Figure 2**), located 3 km to Longchi, were used to calculate the debris flow volume. Each gully generated the initial disaster agents based on the debris flow volume calculated (**Table 5**).

Simulation

The 813 debris flow lasted for 17 h, from 4.00 PM on August 13th to 8.00 AM on August 14th. The model was designed as one tick in the ABM world equaled 15 min in the real world and was run for 76 ticks for each scenario simulation. A total of 18 different scenarios had been simulated by this study (**Table 6**). Concerning human dynamics in emergency response, each scenario simulation was set to be repeated 50 times. During simulations, all types of agents were allowed to interact with the pre-defined behavior rules (**Figure 3**). The interaction process simulated the 813 debris flow event, and the average number of casualties was used to evaluate the effectiveness of each DRM measure.

The disaster agents in debris flow gullies moved based on the topographic condition. As ticks went by in the ABM world, disaster agents were set to interact with patches around and move to the lower patch, and the water level of the patch was calculated based on the volume or number of disaster agents. Disaster agents would keep moving for 76 ticks until they reached the lowest patch or move outside the calculation boundary. Once resident agents encountered disaster agents, this resident agent would be counted as a casualty (**Figure 4**).

Different DRM measures, including EWS, disaster shelters, and incentive plans, were designed in the ABM model to study their influence on the potential casualty. The EWS would affect the initial time of resident evacuation. In 2010 when the 813

TABLE 5 | Attributes of disaster agents.

Gully locations	Area (km^2)	Accounting for the total area (%)	Volume (m^3/tick)	Number of disaster agents
1	7.36	9.42	16855.06	17
2	8.79	11.25	20121.38	20
3	1.75	2.24	4007.41	4
4	1.97	2.52	4504.45	5
5	7.64	9.78	17496.16	17
6	6.26	8.02	14342.13	14
7	20.32	26.01	46523.58	47
8	5.83	7.47	13359.85	13
9	3.56	4.56	8149.29	8
10	4.06	5.19	9285.11	9

TABLE 6 | Summary of scenario simulation and results.

Case No.	Scenarios	Parameter		Casualties
1	**813 event**	**Without EWS (actual situation in 2013)**		**481**
2		**With EWS**		**337**
3	EWS	EWS credibility	1	368
4			2	343
5			3	339
6			4	328
7			5	321
8	EWS + Shelters	Walking distance to shelter	< 10min	315
9			< 30min	337
10			< 60min	324
11			> 60min	335
12		Facilities conditions	not sure	346
13			few	354
14			some	335
15			many	320
16	EWS + Incentive plans	Allowance	5 CNY	330
17			20 CNY	328
18			50 CNY	323

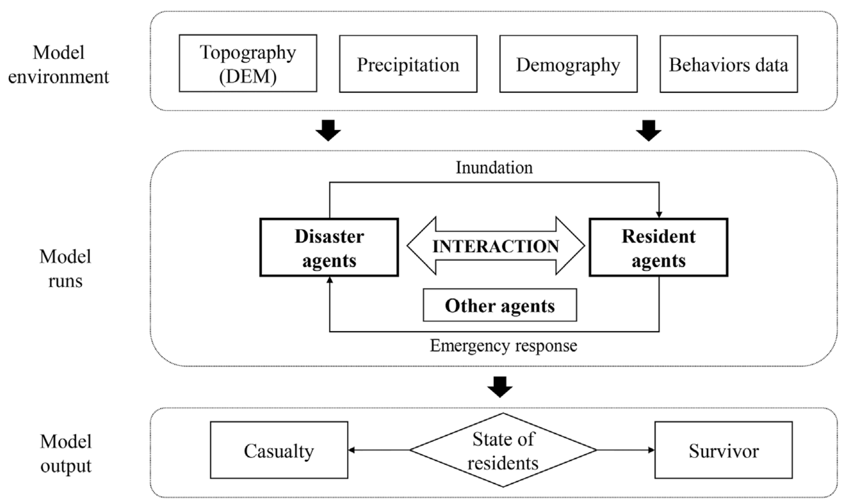

FIGURE 3 | The ABM model considering interactions among environment and agents.

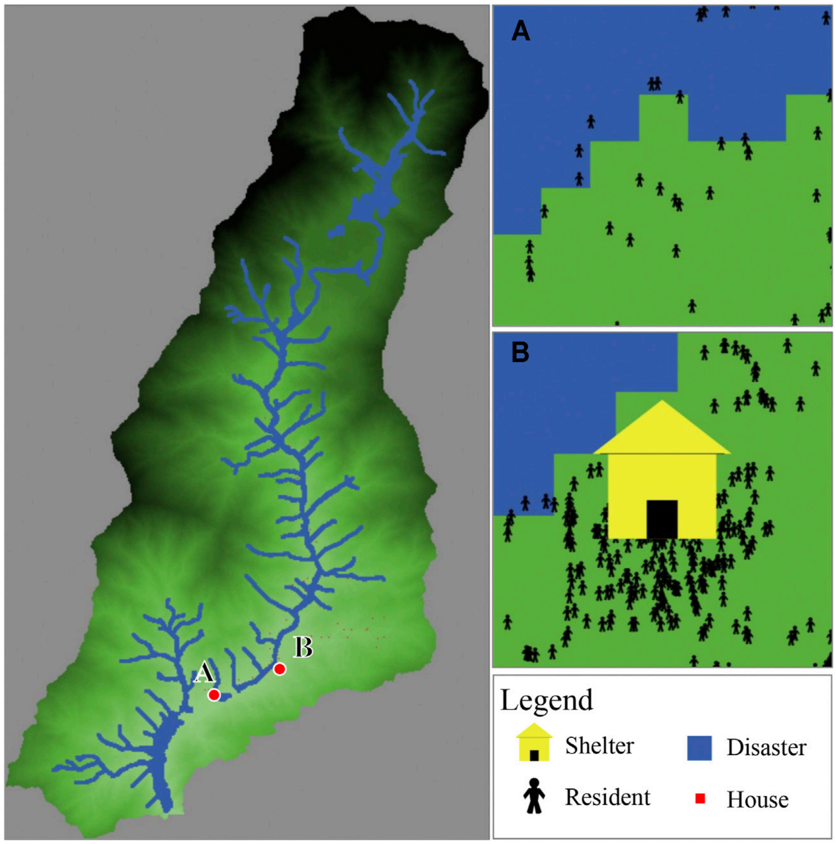

FIGURE 4 | Simulation Case No. 10: **(A)** Residents encountered disaster (man in a blue patch); **(B)** Residents reach the shelter.

debris flow occurred, there was no EWS available. In this case, the model only allowed resident agents to start the initial emergency response process when the disaster agent appeared in their sight. On the contrary, when the EWS became available, the warning was released 2 h (8 ticks) before the debris flow occurred. It was assumed that all residents could receive alerts and immediately start the emergency response based on their behavior rules. Shelter and incentive plans were set to affect their emergency response. Resident agents would decide which destination they move to base on their perception of the disaster shelter. The incentive plans were to help raise the evacuation willingness of residents after they received disaster warnings. The effectiveness of disaster shelters and incentive plans in casualty reduction was generated assuming that the EWS was available in this model.

RESULTS

Different DRM scenarios were simulated by the proposed model (**Table 6**). Each scenario was repeated by 50 times, and the average number of casualties was calculated. The case of 813 events without EWS (Case No.1 in **Table 6**) represented the actual disaster situation in 2013 and generated the number of potential casualties in this scenario (481). In addition, EWS were often implemented along with other DRM measures to supplement each other. In this paper, two types of DRM measures were adopted to explore their effectiveness through the change in casualty, which was 1) provide disaster shelters and 2) set up incentive plans for evacuation. The potential casualties of each scenario are summarized in **Table 6** and elaborated in the following sections.

DRM Measure 1: Early Warning System

This study first explored the effect of installing EWS as the DRM measures (**Figure 5A**). The average casualties significantly decreased from 481 to 337, by 30% compared with no EWS was available. As practices have proved that the EWS could not always bring about early actions (Zaki et al., 2019), this study further explored how the credibility of the EWS can affect the effectiveness of the systems. The 5-point Likert-Scale questions were used to obtain the public perception of the credibility of EWS, among which point 1 was the least credible, and point 5 was the most credible. **Figure 5B** showed that with the increase of EWS credibility (1–5), casualties dropped from 368 to 321. It can be seen that the public perception of the EWS credibility is influential to its effectiveness. To quantify the influence of other DRM measures in this section, 337 (casualty from case 2 in **Table 6**) was set as the baseline of assessment. When the public was very satisfied (point 5 on **Figure 5B**) with the credible EWS,

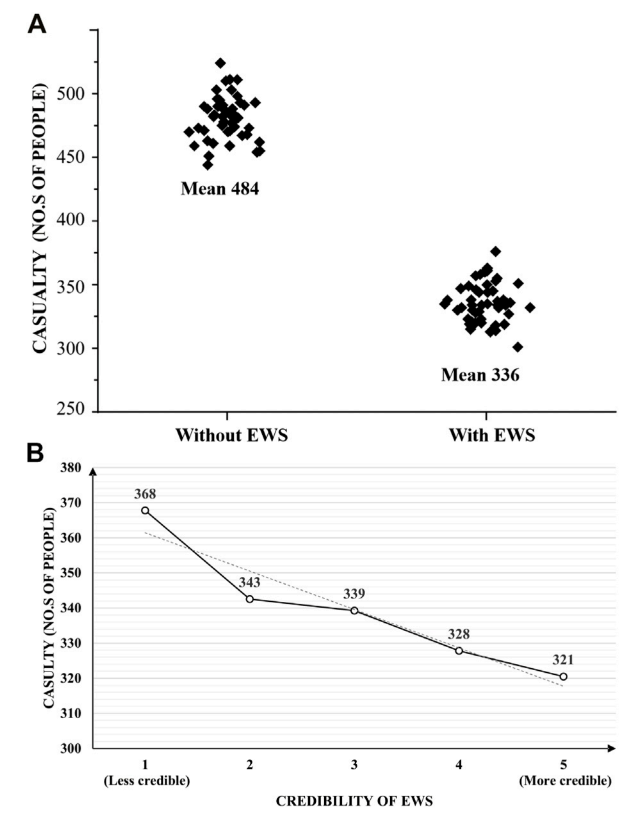

FIGURE 5 | EWS and potential casualties: **(A)** without and with EWS; **(B)** credibility of EWS.

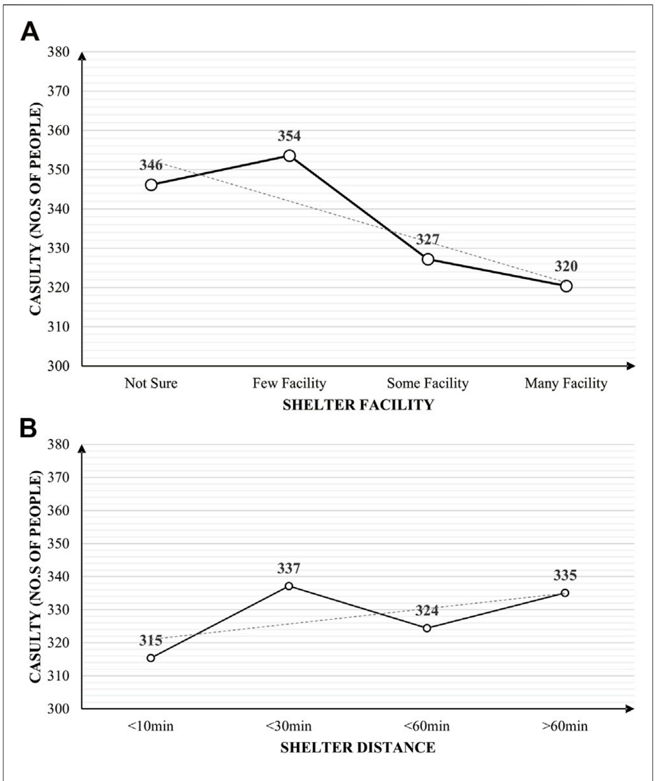

FIGURE 6 | Potential casualties with different shelter settings: **(A)** walking distance from residents to shelters; **(B)** shelter facilities.

casualties could be further reduced by 5%, from 337 to 321. On the contrary, less credible EWS would cause the casualties to increase by 8%, from 337 to 368.

DRM Measure 2: Early Warning System With Disaster Shelter

Disaster shelters provide residents with a safe place during disaster events. Public perception of the shelter design, such as distance to the current location and facilities provided in the shelter, would affect residents' choices on the evacuation strategy and result in different casualties. The impact of public perception on shelters design was studied from two aspects: distance from home to shelters, and facilities provided in the shelter.

For public perception on the distance, this study divided the distance from their location to the shelter into four degrees: "<10min walking" (very close), "< 30 min walking" (close), "< 60 min walking" (far), and "> 60min walking" (very far). The number of casualties varied in the range of 315–337 (**Figure 6A**). The lowest casualties 315) occurred when people felt very close to the shelter, with a casualty reduction rate of about 34% compared to no EWS 481) and 6% compared with EWS alone (337). For the public perception of the facilities provided in the disaster shelters, this study categorized the results into four groups: "few facilities" (basic living needs), "some facilities" (living and medical needs), "many facilities" (living, medical needs, and entertainment), and "not sure" (no idea of what facilities were provided). The results showed that casualties varied from 354 to 320 (**Figure 6B**). Generally, as shelter facilities improved, the potential casualties reduced. The lowest casualties (320) occurred when there were many facilities available in the shelter with a casualty reduction rate of about 33% compared to no EWS (481) and 5% compared with EWS alone (337).

DRM Measure 3: Early Warning and Incentive Plans

The Longchi government set up incentive plans to encourage residents to evacuate after receiving the alert from the EWS. A small number of living expenses was provided to residents who reached the disaster shelter immediately after the EWS. The study found that most respondents showed a positive attitude toward the incentive plan and reported that this measure could attract them to cooperate with the EWS. This study conducted three scenarios where residents were provided with 5 CNY, 20 CNY, and 50 CNY, respectively, and obtained the number of casualties under each scenario.

The results show that when residents were rewarded with 5 CNY, casualties decreased to 330, further reduced 1.84% compared with EWS alone (**Figure 7**). When rewards increased to 20 CNY and 50 CNY, casualties were 328 and 323, further reduced 1% and 2% compared with when 5 CNY was provided. Although the amount of reward increased dramatically from 5 CNY to 50 CNY, the further reduction of casualties was not significant. Therefore, incentive plans with EWS could help reduce the casualties, but they only worked at a very marginally level.

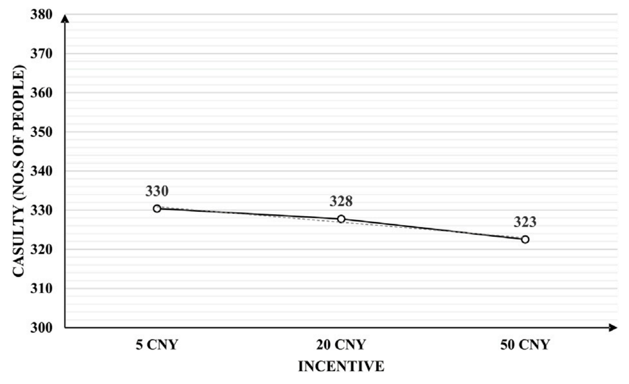

FIGURE 7 | Potential casualties with incentive plans.

DISCUSSION

ABM simulates and encapsulates complex systems from the behaviors and interactions of individual agents. One of the main concerns is whether an ABM represents reality well enough to extrapolate into the future. Models are typically calibrated once, using historical data, then projected forward in time to make a prediction (Ward et al., 2016). Some uncertainties in ABM come from dynamics (changing over space and time), stochastic (containing inherent randomness), and unobserved (unseen from the data) conditions of the real system under study (Kieu et al., 2020). The extent of ABM can be validated to reduce the uncertainty through calibration using historical data (Bonabeau, 2002). Therefore, this study adopted the 813 debris flow events data and calibrated the proposed ABM model to best fit the disaster scenario with the local context of Longchi town. However, an agreement between model and data does not always imply that the model accurately describes the processes; it could only indicate that the model is one of several that is plausible to a situation (Papadelis and Flamous, 2019). The model in the current study also suffered from uncertainty such as the population structure, human movement speed during the evacuation, and choices they make when faced with decisions. Studies have found that even a well-calibrated model will diverge from the true state of the underlying system (Clay et al., 2020). In this case, to assure the significance of the conclusion, this study simulated 3,000 entities for each scenario and repeated 50 runs for each scenario. The average of 50 runs was taken as the estimation of the performance measure to reduce the model uncertainty as much as possible.

EWS Was Essential for Community-Based DRM, and Its Credibility Was Critical to Its Effectiveness

EWS is one of the highly-praised DRM measures widely used worldwide. Based on the 813 debris flow simulations, this study found that having EWS could reduce casualties by up to 30%. Since there was no EWS in 2013 during the 813 event, the interview found that many people did not evacuate until they had already faced the debris flow. Many casualties were caused due to a lack of time to evacuate. Thus, EWS can provide residents with lead time for early evacuation and save more lives. However, this study also found that the credibility of EWS would seriously affect its effectiveness (**Figure 5**), and it could affect the result by 13%. When the public perception of the credibility of EWS was low, people tended not to trust the alerts and not evacuate at all. Therefore, it was necessary to carry out more in-depth scientific research to understand the mechanism of disaster formation and movement to improve the accuracy and credibility of EWS and ultimately improve the effectiveness of DRM.

EWS Could Be Supplemented by Other Measures to Further Reduce Casualties

EWS could be supplemented by other measures to further reduce casualties and improve the effectiveness of DRM. This study explored the effect of DRM measure and found that disaster shelter and incentive plans could further reduce casualties up to 6% and 4%, respectively, compared with EWS alone.

For disaster shelter, its effectiveness depended on the location of shelter and facilities provided in it. Distance between shelter and resident location would affect their willingness to evacuate. When the walking distance from home to the shelters was within 10 min, residents were more willing to evacuate, which resulted in a casualty number at 315. Building shelters closer to residents could raise public evacuation willingness and result in fewer casualties. At the same time, from case No. 12 to No. 15 in **Table 6**, it can be seen that facilities provided in the shelter also affected its effectiveness by 9%. When the shelter facilities were diversified with living, medical, entertainment facilities, the number of potential casualties could be minimum, while in the case of only basic living being provided, the potential casualties increased.

Since not all residents are willing to evacuate immediately after receiving early warning information, the incentives plan can help them comply with EWS. However, this study showed that increasing the amount of incentive does not effectively reduce casualties further. In this case, residents' annual income per capita was 8,594 CNY (Dujiangyan Government, 2021). When the incentive increased from 5 CNY to 50 CNY, it could only reduce casualty from 330 to 323, by 2%. Therefore, though the DRM measures could be improved by providing incentive plans for evacuation, the marginal effect was obvious, and raising the allowance could not significantly reduce the casualty.

The Downside Effects of Other DRM Measures to EWS Might Exist

With all kinds of DRM measures, although the potential casualties were all lower than that of the 813 event (**Table 6**), this study found that there were cases that resulted in more casualties than that of setting up EWS alone. The simulation showed that in some cases, the location and facilities of shelters might constrain the effectiveness of EWS. For example, in the case No.11 and No.13, when shelter distance >60 min or very few facilities were provided in the shelter, there were more casualties (335 and 354 respectively) than that of setting up EWS alone (337). One possible reason could be that the interview showed that when the distance to the shelter was more than 60 min, residents were reluctant to evacuate and tended to walk to nearby "assumed safe places" based on their own judgment, which could lead to potential casualties in the model. In addition, when residents were unsure what kind of facilities were provided or knew there was only basic living, they were more reluctant to evacuate to the shelter or return home from the shelter after evacuation, which caused the increase of potential casualties. Therefore, it was necessary to carefully design DRM measures by considering various human factors in the implementation process to manage their possible downsides effects. Otherwise, spending a large amount of money would, on the contrary, reduce the effectiveness of EWS.

CONCLUSION

By integrating comprehensive components and mechanisms, the DRM measures are complicated with multiple approaches and numerous influential factors, and therefore it is challenging to quantify the effectiveness. This study developed an ABM evaluation model to consider each resident's individual differences and simulated their behaviors during the disaster event, and took the EWS as an example of DRM measures to evaluate their effectiveness in casualty reduction.

This study showed that the EWS was an effective tool in community-based DRM, and its credibility was critical to its effectiveness. Credible EWS could reduce the casualties by as much as 33%, from 481 to 321. In addition, when the EWS was supplemented with other measures such as disaster shelter and incentive plan, the casualties could be further reduced by 6%, from 337 to 315. However, its effectiveness was largely affected by the public perception of the design and implementation of those measures. Therefore, when designing disaster shelters, priority should be given to place shelters as close as possible to residential areas. When the resource was adequate to optimize shelter effectiveness, the needs of residents, not only the basic living but also medical care, communications, entertainment, should be considered. To create a more effective incentive plan, resident income should be assessed to provide a design reference. The marginal effect of incentive plans on casualty reduction also should be recognized to avoid wasting resources.

To conclude, human dynamics have a significant impact on the effectiveness of DRM measures. Therefore, stakeholders need to choose proper and effective DRM measures considering local conditions, such as risk perception, education levels, and disaster knowledge. The present study developed a quantitative analytical model to assess the effectiveness of EWS and related DRM measures in terms of casualty reduction. It could provide a tool for stakeholders to develop an evidence-based and risk-informed DRM strategy that best fits the resources.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors without undue reservation.

AUTHOR CONTRIBUTIONS

Conceptualization, SW, YL, SY, and PC; Methodology and formal analysis, SW, SY, and YL; Data preparation, WJ, and all authors contributed to writing and editing the manuscript.

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Time-Dependent Framework for Analyzing Emergency Intervention Travel Times and Risk Implications due to Earthquakes. Bucharest Case Study

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Earthquakes can generate a significant number of casualties within seconds, as well as high economic losses. The lack of rapid and coordinated emergency intervention can contribute to much greater losses. In this paper we develop a framework taking advantage of the ArcGis Network Analyst extension, able to account for post-earthquake conditions and reflect travel times. By combining 1) network characteristics with 2) direct seismic damage information, 3) models to determine road obstruction potential, 4) traffic information and time-dependent post-earthquake modeling but also 5) emergency intervention facilities (hospitals or fire stations) and considerations regarding their functional limitations, this framework can provide important support for the management of emergency intervention but also for risk reduction planning. Main results consist of maps showing travel times for various scenarios and moments after an earthquake, inaccessible areas, vital roads for access or an identification of important facilities. As case study we chose Bucharest, one of Europe's most endangered capitals considering the seismic risk level. The city was and could be considerably affected by earthquakes in the Vrancea Seismic Zone, being characterized by a high number of vulnerable buildings and by one of the greatest typical traffic congestion levels in the world. Compared to previous network studies for Bucharest, the new approach is more complex and customable, providing means for real-time integration and time-dependent analysis. Results, for a worst-case scenario, prove that the risks could be even greater than expected, but also what should be done to mitigate them, such as the construction of a new hospital in the western part of the city, ensuring safe delimited routes for emergency vehicles or expanding the treatment capacity of actual hospitals—some of which also need seismic retrofitting. Results of this study will be integrated in the revised version of the National Conception for Post-Earthquake Response—an operational framework which will lead to risk mitigation through the improvement of post-disaster reaction.

Keywords: seismic risk, infrastructure, GIS, emergency management, Bucharest, network, time-dependent, earthquake

INTRODUCTION

Transportation networks are strategically crucial to the post-shock recovery and resilience. As demonstrated by several recent real-world seismic events (among which Wenchuan, China, 2008; Haiti, 2010; Maule, Chile, 2010; Tohoku, Japan, 2011; Gorka, Nepal, 2015; Central Italy, 2016 or Sulawesi, 2018), road networks have turned out to be vulnerable both directly and indirectly, contributing to significant additional losses. Problems can vary depending on location (urban or rural), scale (structural or systemic) and damage type (direct or indirect). Of particular relevance to the improvement of emergency intervention management is the time-dependent status of the systems considered and the quality and quantity of information relating to such status. This usually increases and changes in nature as time from the disruptive event elapses but can also be affected by secondary events as time progresses, overlapping the immediate response and recovery phases. An adaptive time-dependent framework for analyzing emergency intervention travel times will enable relevant stakeholders to identify specific risks of interest and formulate relevant coordinated demands for preparedness and response actions.

In order to mitigate the risks due to delayed response, a good understanding of intervention capabilities as well as travel times under various conditions is needed. The possibility of integrating live data regarding traffic, incidents or the status of emergency facilities and vehicles—taking advantage of recent technological progress (from IoT devices to big data analysis but also with regards to crowdsourcing, as described in Finazzi, 2020), should be one of the key inputs to be considered in the methodological development. By analyzing recent articles in the field of study, among which Franchin et al. (2006), Pinto et al. (2012), Miller (2014), Jenelius and Mattsson (2015), Hirokawa and Osaragi (2016), Hackl et al. (2018), or Rohr et al. (2020) and evaluating recent earthquakes, we identified some of the main aspects to consider when modeling travel times after earthquakes, in order to evaluate the performance of the rapid response:

- Medical treatment facilities (such as hospitals), characterized by location, structural or functional vulnerabilities (including back-up systems in case of emergencies or reach-time to work place for personnel), specialties (more or less relevant for specific emergencies), staff characteristics, number of beds, equipment, ambulances etc.;
- Facilities for emergency intervention (such as fire-stations or operative centers), characterized by location, structural or functional vulnerabilities, number and type of vehicles (with various features), staff characteristics, equipment etc.
- Directly affected infrastructure components (from bridges to traffic-lights - also due to blackouts) and road incidents, all with implications on traffic flow; these could be reported in the various applications currently available, making a real difference—if data communication would still be functional;
- Affected areas where intervention might be needed, number of potentially affected people, demand for specific rescue forces and on-site accessibility for rescue vehicles;
- Identification of roads potentially obstructed by building debris, based on street characteristics (**Figures 1A,B** illustrates some of the problems in Bucharest, right after the 4 March 1977 earthquake);
- The potential effects of aftershocks and the multi-hazard and multi-risk dimension;
- Traffic pattern changes: A modelling of initial traffic values and post-earthquake modifications (using the previously mentioned aspects), which can be related to multiple causes such as the people desire to ensure that their relatives or assets are safe, people evacuating affected areas or entering them with rescue or transit purposes, people in need to reach their jobs as responsible in emergency situations etc. In many cases, post-earthquake traffic is characterized by the violation of circulation rules. For a real account of the situation, live data crowd-sourced or from emergency vehicle's GPS devices and traffic monitoring devices would facilitate a good understanding of the traffic status and proper management decisions, as well as validation for traffic models. The analysis could also account for various traffic management decisions.

Given that hospitals play one of the most important roles in post-earthquake situations—on them depending the save of many lives in express need of medical care, we consider as a necessity to focus on these facilities and travel times from and toward them. Recent experiences in our case study area Bucharest but also in other areas highlight important aspects to consider, regarding the risks of medical treatment facilities:

- Structural and non-structural damage of hospitals, as well as limited patient treatment capacity and shortage of medical personnel are significant threats. These can render a hospital not functional at some point after the earthquake and lead to the necessity of a viable alternate solution. That is why in an important performance indicator should refer to the availability of other hospitals to take over the rescue effort. As real experiences in Bucharest, we mention that after the 4 March 1977 Vrancea earthquake, the 1,500 patients of the Floreasca Clinical Emergency Hospital needed to be evacuated 1 day after the earthquake, given that after rapid structural inspection the building was considered unsafe (**Figures 1C,D**).
- Not all hospitals can cure typical wounds due to earthquakes. As Hotz et al. (2011) shows, for the Haiti earthquake in 2010 the most common injury diagnoses due to earthquakes are fractures/dislocations, wound infections, and head, face, and brain injuries. The most common injury-related surgical procedures were wound debridement/skin grafting, treatment for orthopedic trauma, and surgical amputation. In case of fires due to earthquakes, also burns will need to be treated.
- The mistreating of patients with medical problems (example: The case of patients with severe burns affected by nosocomial infections, after the Colectiv Club fire in Bucharest—Marica, 2017)

FIGURE 1 | Damage due to the 4 March 1977 earthquake in Romania, leading to the blockage of streets [**(A,B)**; source: Malide Cristian/muzeuldefotografie. ro] and to Floreasca Clinical Emergency Hospital evacuation **(C,D)**. The figure also presents actual problems in Bucharest: vulnerable buildings **(E)** and traffic congestion **(E,F)**, the importance of delimited tramway lines accessible also to emergency vehicles **(F)** and ambulance queue formed in front of the Floreasca Clinical Emergency Hospital due to multiple COVID-19 cases **(G)** (source: Lapovita Ana).

- The chaos in and around the hospitals could be a significant issue, right after earthquakes. In the case of Floreasca Clinical Emergency Hospital, located close to affected areas, in the first hour following the 1977 earthquake road access was very difficult and had to be handled by volunteers (Buhoiu, 1977); also, the COVID-19 pandemic showed this feature during the peak of its waves (**Figure 1G**).
- Additional risk in the context of the COVID-19 pandemic. Some hospitals or some of their sections are devoted, starting with 2020, to the treatment of COVID-19 patients only. Many hospitals are overcrowded especially during surges, so the collapse and potential fire outbreak (with increased vulnerability due to substances for ventilation) could lead to multiple victims—not to mention the loss of vital medical personnel. In 2020 and 2021, fires occurred in 11 hospitals in Romania (Milonean, 2021), especially in the intensive care units—without the contribution of earthquakes. In case of hospital evacuation, the limited relocation capabilities, the potential mix of patients and the neglecting of pandemic rules (sometime forced by the circumstance, as earthquake are hazards of surprise) can lead to a significant increase of COVID-19 cases. Hygiene problems can also be a major issue. The recent experience of the March 2020 earthquake in Croatia was documented to not have caused a significant increase in COVID-19 cases following the event (Čivljak et al., 2020), although many hospitals needed to be evacuated, among the patients being 22 persons confirmed with COVID-19. The Haiti earthquake in August 2021 showed a different facet: that a large number of medical facilities destroyed (66 in Grand'Anse, Nippes and Sud, following this event) can lead to lack of access to basic services—for 34% of the people in earthquake affected-areas (Bagaipo and Janoch, 2021) and as such to limited vaccination rates; the consequences are yet to be evaluated. The analysis of the Epirus and Samos earthquakes but also the Evia flood and Ianos storm in Greece, in 2020, has shown no major contribution to the increase in the number of COVID-19 cases (Mavroulis et al., 2021), but as authors mention, various circumstances and number of casualties can have high impact on the rate.

In the face of increased exposure, climate change or unpredictable hazards such as earthquakes (which can trigger other hazards), societies have ever complex and bigger challenges in order to improve resilience. As cities, their infrastructures and the means of transportation constantly change, travel time and the analysis of implications on people, economy and development needs to be a continuous effort. Many cities have been significantly affected by earthquakes—Bucharest, capital of Romania, being one of them. Lessons of the past have not necessarily been learned. Much has changed since the previous major events in the Vrancea Zone, on 10 November 1940 (Mw 7.7) and 4 March 1977 (Mw 7.4)—the latest leading to the collapse of 32 moderate and high-rise buildings in the city, the death of 1,424 persons (90% out of the national total) and a 70% percentage of the total economic losses. Traffic is now a significant problem (**Figures 1E,F**)—Bucharest being ranked in terms of typical congestion level on the 11th place by INRIX

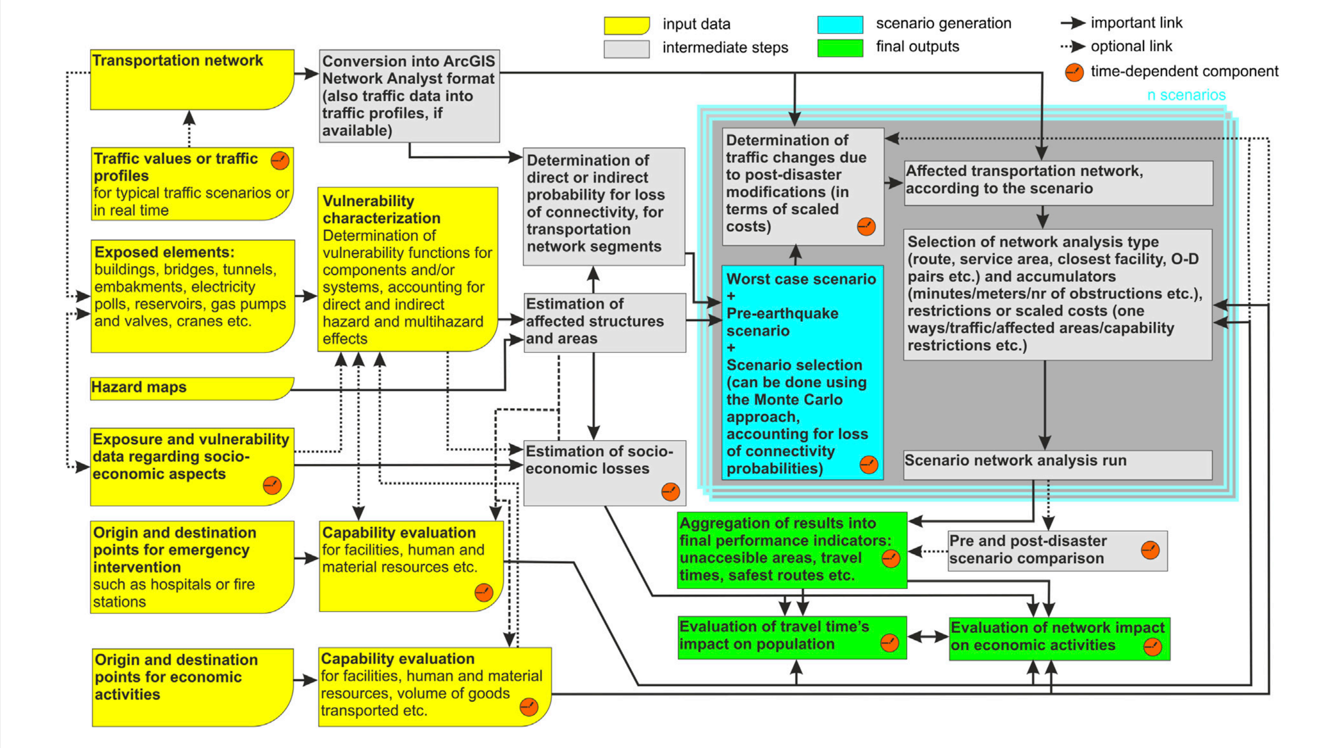

FIGURE 2 | Flowchart of the framework, including time-dependent component classifications (modified from Toma-Danila et al., 2020).

(2021) out of 1,000+ cities, after being on the 2nd place in 2020, and on the 18th place by TomTom (2020) out of 416 world-wide. The very high seismic vulnerability of many buildings (including hospitals and fire stations), accompanied by limited access for emergency intervention in many areas due to the high number of cars parked illegally, could be the recipe for a greater disaster. Recent studies (such as Ianoş et al., 2017, Pavel et al., 2018, Toma-Danila, 2018, or Toma-Danila et al., 2020) have showed the need to improve emergency intervention access and planning in Bucharest.

In this article, our objective is to make additional steps toward a standardized and flexible time-dependent analysis, with applicability in legal procedures and near-real time implementation. New modeling components are added, such as the impact of delimited routes recently introduced for tramways but also emergency intervention vehicles (**Figure 1F**), a larger dataset of vulnerable buildings in Bucharest, more recent and reliable traffic data, a detailed dataset regarding hospitals and their importance in case of earthquakes as well as a quicker procedure for integrating OpenStreetMap road data and traffic values (with applicability to many other study areas).

The analysis, which will contribute to a new version of the Network-Risk toolbox (with the previous presented in Toma-Danila et al., 2020), is built upon ArcGIS with the Network Analyst extension. Its objective is the improvement of emergency intervention management in Romania, reflecting the need for less vulnerable and new hospitals, seismic retrofitting of residential buildings and traffic management planning in post-earthquake situations but also in typical conditions. Results are shaped to fit the needs of the National Conception for Post-Earthquake Response—an operational procedure used by the General Inspectorate for Emergency Situations in Romania, aimed to ensure a proper planning of intervention in post-earthquake conditions, which will be soon revised based on our input. As an additional connection, our analysis can be used to verify if the time frame mentioned in the National Law 95/2006 is eloquent in crisis situations. This states that the organization of qualified first aid services must ensure a maximum reach time (counted from the emergency call time) not exceeding 8 min in urban areas, for more than 90% of cases, and 12 min in rural areas, for more than 75% of cases.

METHODS AND DATA

Flowchart of the Framework

When developing a decision-support system based on the analysis of travel times, multiple inputs and methodologies need to be considered. As **Figure 2** shows, we refer in our framework to the following inputs:

- Road networks: we expand on this type of transportation network given that it is still the most used for the emergency intervention access. However, it could easily be replaced by railways or waterways. Off-roads can also be defined as well as multi-modal transportation.
- Traffic scenarios: Whether typical, specific or real-time data;

- Data regarding buildings and infrastructures damaged in various degrees by the mainshock and aftershocks (estimated or validated), but also by other types of hazards (such as tsunamis or landslides);
- The implication of building and infrastructure damage (as well as triggered hazards) on road network functionality loss, through an evaluation of debris potential to block the roads and changes in traffic patterns;
- Various facilities (hospitals, fire stations) with different functionalities but also resilience indicators;
- Various emergency units' availability over time and restrictions (such as width of a street for access);
- Origins and destinations for economic activities, in order to further calculate the economic impact of network disruptions. Cost-benefit analysis could also be considered, with regards to aspects such as the suitability of building a new hospital versus consolidating an existing one, including location-based criteria.

The framework described in this article expands and improves the framework presented in Toma-Danila et al. (2020), making it also significantly different from other frameworks such as Pinto et al. (2012), Hirokawa and Osaragi (2016), or Rohr et al. (2020). Our approach also builds upon the previous work of Sun et al. (2021), novelties consisting of:

- The use of the historical traffic feature (ESRI, 2021; compared to using individual columns for cost computations), therefore providing an easier time-dependent analysis– both easy to define using traffic profiles and continuous (enabling simulations for earthquakes at any hour with limited amount of parameter recalculations);
- A new approach for calculating which road segments are partially of fully blocked by building debris;
- For network analysis, we now recommend and use the concept of barriers and scaled costs, which is more straight-forward than the previous ways of using special columns with times for each time interval and additional cost definitions (which could still be used however for tasks such as counting how many difficult to cross areas will be encountered);
- A computer-assisted methodology for converting rapidly free OpenStreetMap road data into the ArcGIS network format.

The framework is tested in ArcGIS with the Network Analyst extension—a popular commercial choice for complex network modeling. Among the recent studies relying on it, partially similar to our approach, we mention Sevtsuk and Mekonnen (2012), Shahabi and Wilson (2014), or Rohr et al. (2020). ArcGIS uses as shortest-path routing algorithms the widely used Dijkstra algorithm (ESRI, 2021), which provides a good balance between computational time and accuracy (Fan and Shi, 2010); optimized approaches such as hierarchy preferences are a good feature for testing large network datasets. The integration of other algorithms such as A*, Bellman-Ford, Floyd–Warshall or Johnson would be a good addition for research—ArcGIS's Python script compatibility setting good premises. We chose ArcGIS due to its already available spatial analysis and network modeling functionalities but also GIS representation capabilities, which allowed us to test multiple input data setups, but also because it eases the use and customization for other interested researchers. ArcGIS's Network Analyst extension also has the option to account for live traffic—by incorporating speed values from dynamic traffic format (DTF) files. Nevertheless, our framework could be also embedded using QGIS (making use of the QNEAT3 plugin) or Matlab's graph and network algorithms.

Input Data for Bucharest

The data used in this study consists of:

- OpenStreetMap (OSM) vector road network of Bucharest and surroundings (**Figure 2**) from October 2021, downloaded from the Geofabrik GIS Data Portal (http://download.geofabrik.de) and reprocessed in ArcGis Network Analyst format through an almost fully automated procedure described in the Network-risk toolbox manual (Toma-Danila and Tiganescu, 2021). Compared to our previous studies (Toma-Danila et al., 2020 or; Toma-Danila, 2018), which used OSM road data from January 2016, October 2021 data has some important additions such as the A3 highway, the Nicolae Grigorescu passage or the Ciurel Passage. The chosen road network extent is also larger, allowing the analysis of many cities close to Bucharest, with significant dependencies on it. Given that emergency intervention vehicles can legally circulate on the asphalted specially delimited tramway lines (**Figure 1F**)—which creates a separate and generally safe (therefore faster) alternative access route, we identified and included these segments in the road network (**Figure 3**).
- Typical traffic is still a major issue (TomTom, 2020)—also in the COVID-19 period (INRIX, 2021), in which, except for lock-down intervals, people used cars more often, given considerations regarding an increased exposure in public transport vehicles. Measures taken in the last years, such as stricter regulations for parking space in the city center, opening of underground parking lots and installation of pavement blockers have reduced the amount of traffic lanes blocked by illegal parking, but still there are significant issues limiting the road's functional space (too many cars and to less care about the law). As typical traffic data we used Area Analysis Data from TomTom Traffic Statistics available *via* TomTom's MOVE portal (TomTom, 2021), averaged for the 1 to 21 April 2019 (with orthodox Easter being on 28 April 2019 so no major influence of holidays being induced). Data was available only for the 1-3 Local Time (LT), 8-10 LT and 16-18 LT intervals. To differentiate between weekdays and weekends we used as proxy 0.6 respectively 1.2 multiplication factors to average speeds, deduced from result comparison with Google Maps typical traffic queries for representative routes. Given that TomTom road data for which traffic data is available is different from OSM data (including only important roads), we used the *near* function in ArcGis to associate the closest

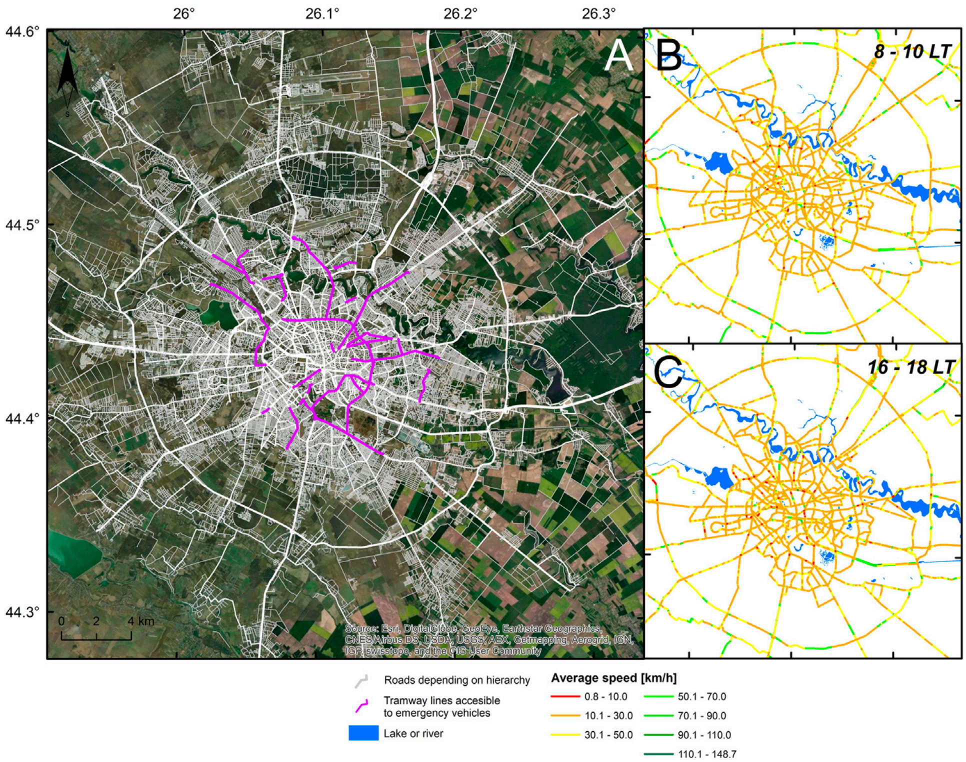

FIGURE 3 | OSM road network for Bucharest and surroundings, used in this study **(A)** and typical traffic values according to TomTom data **(B,C)**, showing the TomTom less complex road network, comprising of higher hierarchy roads.

average speed values to the OSM road segments (for segments closer than 200 m), giving satisfactory results. For other segments we applied the OSM maximum speed and for tramway road-accessible segments we used the 50 km/h speed. In order to generate 24/7 profiles in ArcGIS, we relied on the TomTom values but also adjusted some profiles based on local knowledge and Google Maps traffic verification for some time intervals.

- A new dataset regarding all hospitals (both public and private) in Bucharest and Ilfov nearby county– a significant extension from the dataset used in previous studies such as Toma-Danila (2018) and Toma-Danila et al. (2020). This also provides information regarding treatment capabilities, in earthquake emergency situations or not. Based on it and the feedback of people involved in disaster medicine we classified hospitals in terms of importance in case of earthquakes, considering both treatment capacity, available personnel and an expert-based evaluation of typical destinations for ambulances. For some hospitals, an evaluation of seismic vulnerability is provided. Currently, among the hospitals acknowledged by expertise to have significant seismic vulnerability in Bucharest (ISUBIF, 2021) are the Bagdasar-Arsenie Emergency Hospital, the Gorgos Psychiatry Hospital (Titan) and the Bucur Maternity—in seismic risk class (SRC) I—the greatest probability of collapse, the Fundeni Clinical Institute's B building, housing 1,000 patients and 2000 medical personnel, with SRC II (still considerable collapse probability) and the Floreasca Hospital's A building—with SRC II. For many hospitals we don't have public information regarding the results of seismic evaluation.
- Location of (mostly residential) buildings individually evaluated by engineers and classified in SRC I and II (out of IV) or urgency categories (older classification), on official lists from the Municipal Administration for the Consolidation of Buildings with Seismic Risk (AMCCRS), georeferenced by RE:RISE and geo-spatial.org (2021). These are not all highly vulnerable buildings in Bucharest, still they represent a significant typology of buildings which were affected during the 1977 earthquake: high-rise reinforced concrete buildings built before 1940. As the National Census in 2011 shows, there are at least 31,430 residential buildings older than 1947 in Bucharest. Out of these, 295 have at least 6 floors—category shown to be highly vulnerable during the 1940 and 1977 Vrancea earthquakes (Toma-Danila and Armas, 2017). 263 are on the AMCCRS list—115 being in SRC I, 110 in SRC II, 15 in SRC III and 23 being consolidated. Additionally, 26,349 buildings are constructed between 1947 and 1960. The first compulsory seismic design code was introduced in 1963, so the scale of the disaster could be considerable (**Figure 4B** provides glimpses of the situation).

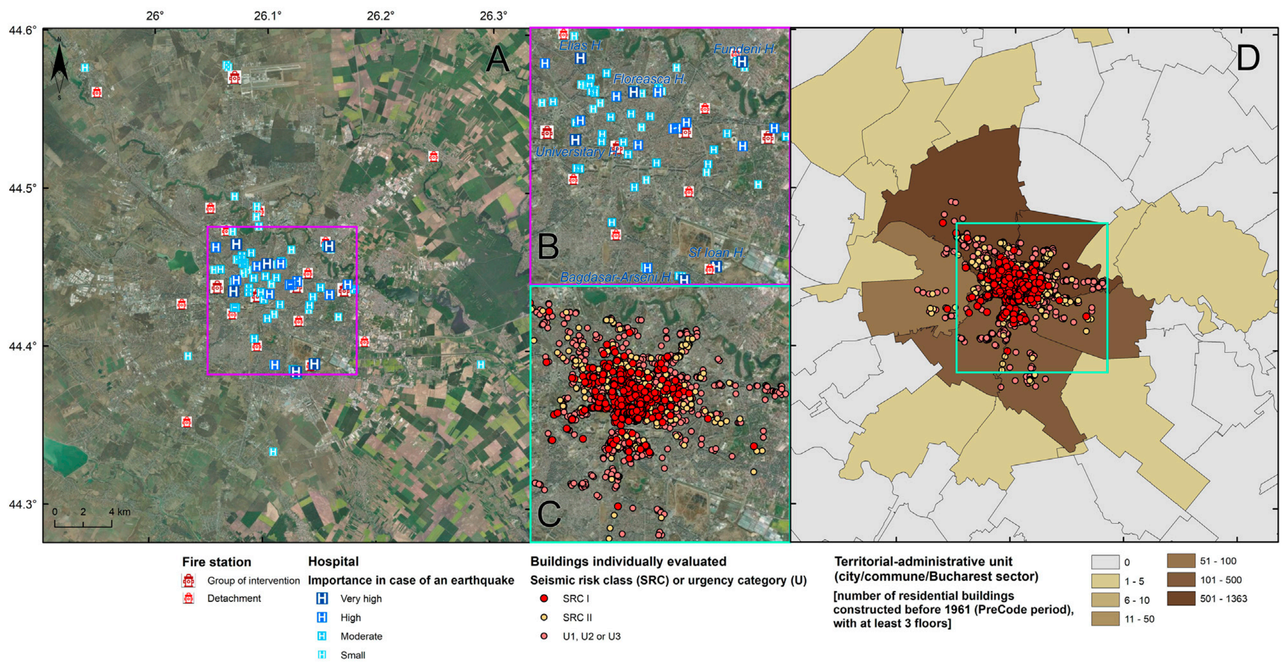

FIGURE 4 | Location of hospitals and fire-stations **(A)** and residential buildings with SRC I, II and in urgency categories as well as number of residential buildings constructed before 1961, with at least 3 floors, according to the 2011 National Data Census, at city/commune/sector level **(D)**. The zoom windows **(B,C)** show the city center and the names of very important hospitals **(B)**.

- For determining the road obstruction potential due to building collapse, we calculated the debris footprint of buildings in SRC I and II and in urgency categories. We used the empirical equation in WP6 of the RISK-UE Project (as mentioned in Franchin et al., 2011), which was determined based on the observations done after the Kocaeli 1999 earthquake for collapsed RC buildings (representative typology also for Bucharest): Debris footprint (meters) = ⅔ * number of floors. This provided satisfactory results, as **Figure 5** shows and also easy implementation for multiple scenarios runs. By converting road polylines into polygons based on their number of lanes and hierarchy we were able to partially automate the process of detecting full or partial obstruction due to building debris. This was done firstly by accounting that some road segments completely blocked by debris split into segments; therefore, by using the ArcGIS erase and intersect functions, identifying afterward the duplicate segments, we found the fully or partially obstructed road segments. We also verified if there are missing segment (completely covered in debris) and re-added them. More complex equations, considering also adjacency of buildings or debris footprint for different building damage states, such as Argyroudis et al. (2015), Zanini et al. (2017) or Yu and Gardoni (2021) will soon be tested in a future paper, also with on-field analysis.
- For bridges, tunnels and passages in Bucharest we did not have damage potential reports available; by applying typical fragility functions from the Syner-G Project, we showed in Toma-Danila et al. (2020) that limited complete damage is expected in Bucharest—as the 1977 earthquake showed. However, by using visual inspection and warning issued also in mass-media, some structures can be considered to a greater degree prone to seismic damage: The Constanta passage but also the Basarab passage, which is relatively new but poorly maintained and due to its long span can have both structural and traffic problems leading to blockage. We tested what could be the travel time impact if these structures collapse.

In order to facilitate the replicability, improvement and integration of data in other studies, both OSM Bucharest network road data in the ArcGIS network format and data regarding hospitals and fire stations in Bucharest and Ilfov county can be retrieved from Mendeley Data (Toma-Danila, 2021a; Toma-Danila, 2021b; Toma-Danila, 2021c).

Modeling Post-earthquake Traffic

This task is one of the most difficult given the many modeling parameters and uncertainties. Detailed procedures have been tested through the time, in studies such as Feng et al. (2021) or Aydin et al. (2018), but still validation with real post-earthquake data is limited. Among the complex systems we mention MATSIM or Simulation of Urban Mobility (SUMO), which was recently used in Costa et al. (2020). The Freeways video game (Captain Games, 2017) and its logic might also provide interesting insights on the problem and solutions. All post-earthquake traffic modeling results can be incorporated in our methodology—in the form of polygons with various scaled

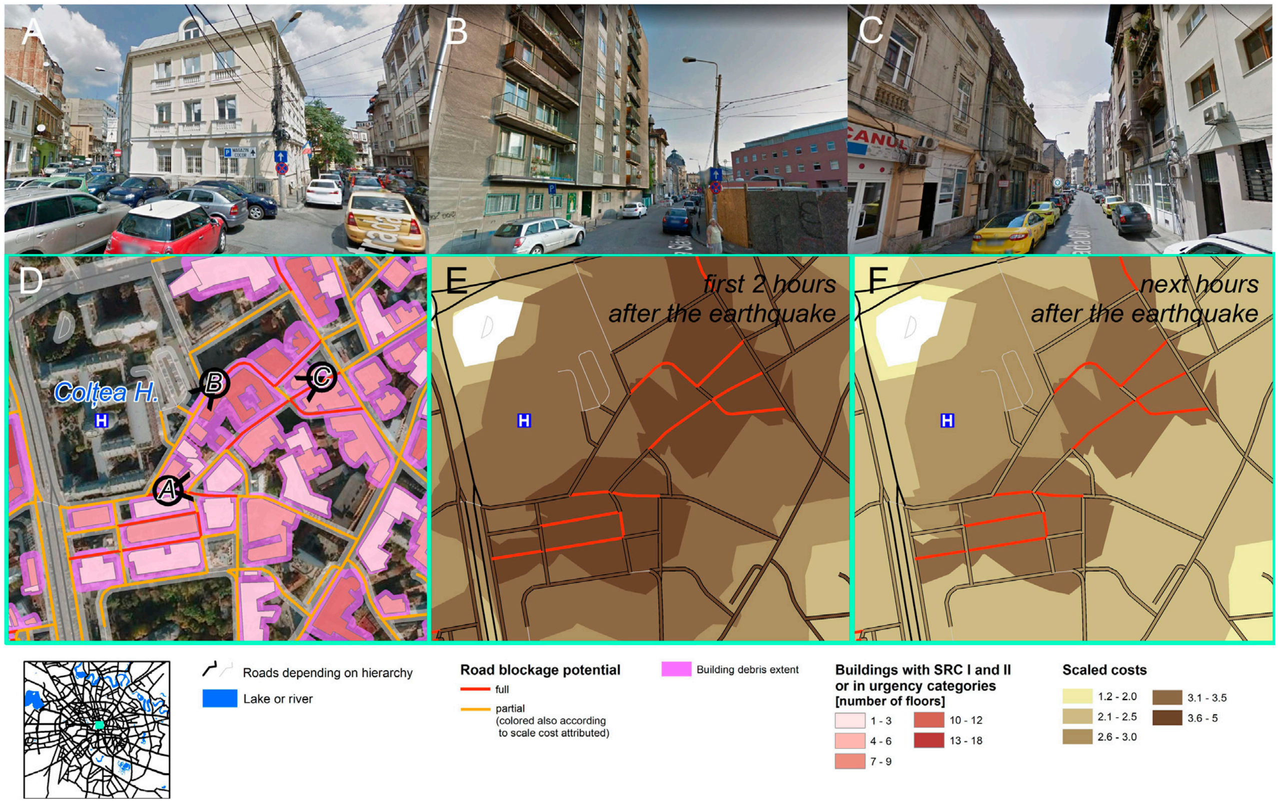

FIGURE 5 | An example of results of the automatic determination of fully or partially blocked road segments due to building debris **(D)** for a central area near the Coltea Hospital, and exemplification of the real situation [**(A–C)**—source: Google Street View). Scaled costs calculated using **Table 1** are also represented **(E,F)**.

TABLE 1 | Scaled costs considered for Bucharest.

Moment after the earthquake	Service area facility	Scaled costs in the service area of:				
		100 m	200 m	300 m	400 m	500 m
First 2 h after	Completely blocked segments	3.5	3	2.5	2.2	2
	Partially blocked segments	2.5	2.2	2	1.8	1.6
	Important hospitals	3	3	—	—	—
	Less important hospitals	2	—	—	—	—
Next 6 h	Completely blocked segments	3	2.5	2.2	1.8	1.5
	Partially blocked segments	2	1.8	1.6	1.4	1.2
	Important hospitals	2.5	2.5	—	—	—
	Less important hospitals	1.5	—	—	—	—

costs increasing the time needed to travel in a specific area. For this study we chose to test a basic yet flexible methodology, following the next steps:

a) Selection of buildings affected by the earthquakes (Monte Carlo approach can be used, as in Toma-Danila et al., 2020);
b) Determination of road segments affected by debris completely or partially;
c) calculation of service areas around these segments in terms of meters. If desired, a differentiation between completely and partially affected segments can be made - as traffic might be more influenced near completely blocked road segments. We used service areas of 100, 200, 300, 400 and 500 m.
d) calculation of service areas around hospitals, with variable meter distance depending on hospital importance. We used 200 m for most important hospitals and 100 m for the others.
e) use of the ArcGIS *union* function to merge all service area polygons (explode multipart features if needed) and assign scaled cost values in a specific column. We used the costs in **Table 1**, after consultations with emergency stakeholders (future incidents—not necessarily earthquakes—could help validate these assumptions, so we will find new solutions for

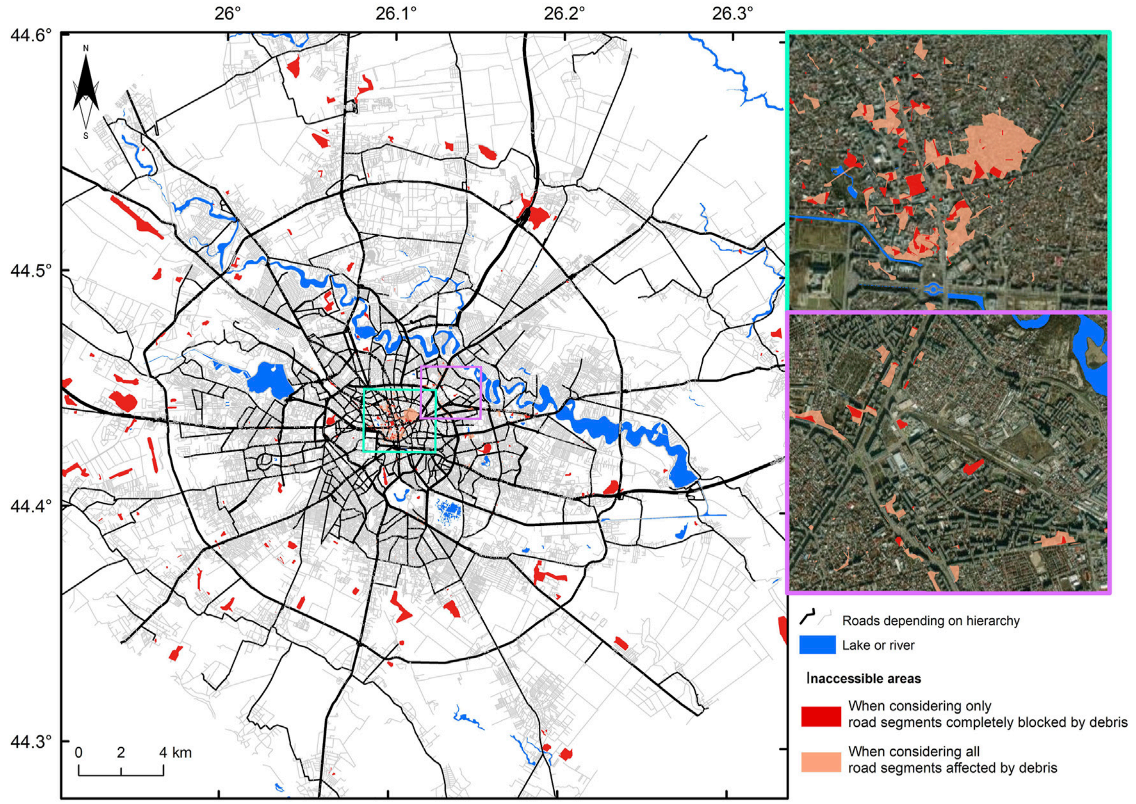

FIGURE 6 | Map showing the potentially inaccessible areas, for the worst-case scenario—all SRC I, II and urgency categories buildings collapsing.

determining analytically these costs). In polygons with multiple scaled costs from different sources we calculated the maximum scaled cost and added an additional cost depending on scaled costs from multiple sources of traffic. Then we summed all potential values (with minimum 4 and maximum 11). For values greater than 7.5 (a highly congested area, judging by the scores) we added to the maximum value 0.5 and for values between 6.5 and 7.4 we added 0.3.

f) Run of Route, Service Area, Closest Facility or O-D cost matrix analysis for hospitals of various importance, with scaled costs for the previously determined service area polygons. Also add to these polygons lines/polygons for road segments affected by buildings: completely blocked segments as restrictions and partially blocked segments with a scaled cost of 5 for the first 2 hours after the earthquake and 3 for the next hours.

RESULTS FOR BUCHAREST

Our study presents a new framework, emphasizing with practical examples its potential. Given that the challenges for Bucharest are significant—both in terms of scale (a 2 million people city plus the surroundings) and risks, our study aims to contribute directly to improving emergency intervention management, fitting within the National Conception for Post-Earthquake Response. As such, we organize our results in subchapters that provide direct answers to questions often asked by emergency responders and planners—relevant also for many other cities.

Which Areas Could Become Inaccessible?

By using service area analysis with detailed generation of polygons, for a greater-than-expected sole break (we used 300 min), areas inaccessible to reach can be identified. For the generation of **Figure 6** (and most of the following figures), we considered a worst-case scenario in which all buildings in SRC I, II and urgency categories are considered to be affected, even though in reality the chances are quite few—at least for complete collapse; however, it is to be kept in mind that beside buildings on the AMCCRS list there are much more vulnerable buildings in Bucharest, as demonstrated above. Given that we had two classifications of building debris impact (fully or partially blocking the roads), we run the analysis and represented the results differently. Given the methodological limitations (the empirical equation for debris area calculation, not considering the adjacency of other buildings—epistemic uncertainty, as **Figure 5B** shows for a segment considered to be partially blocked), but also aleatory uncertainty, it is safer to consider a wider extent of the inaccessible area and not just the red polygons. In this way, a significant potentially inaccessible area in eastern part of the city center can be identified, but also other areas relatively great in size (the minibox of **Figure 5**).

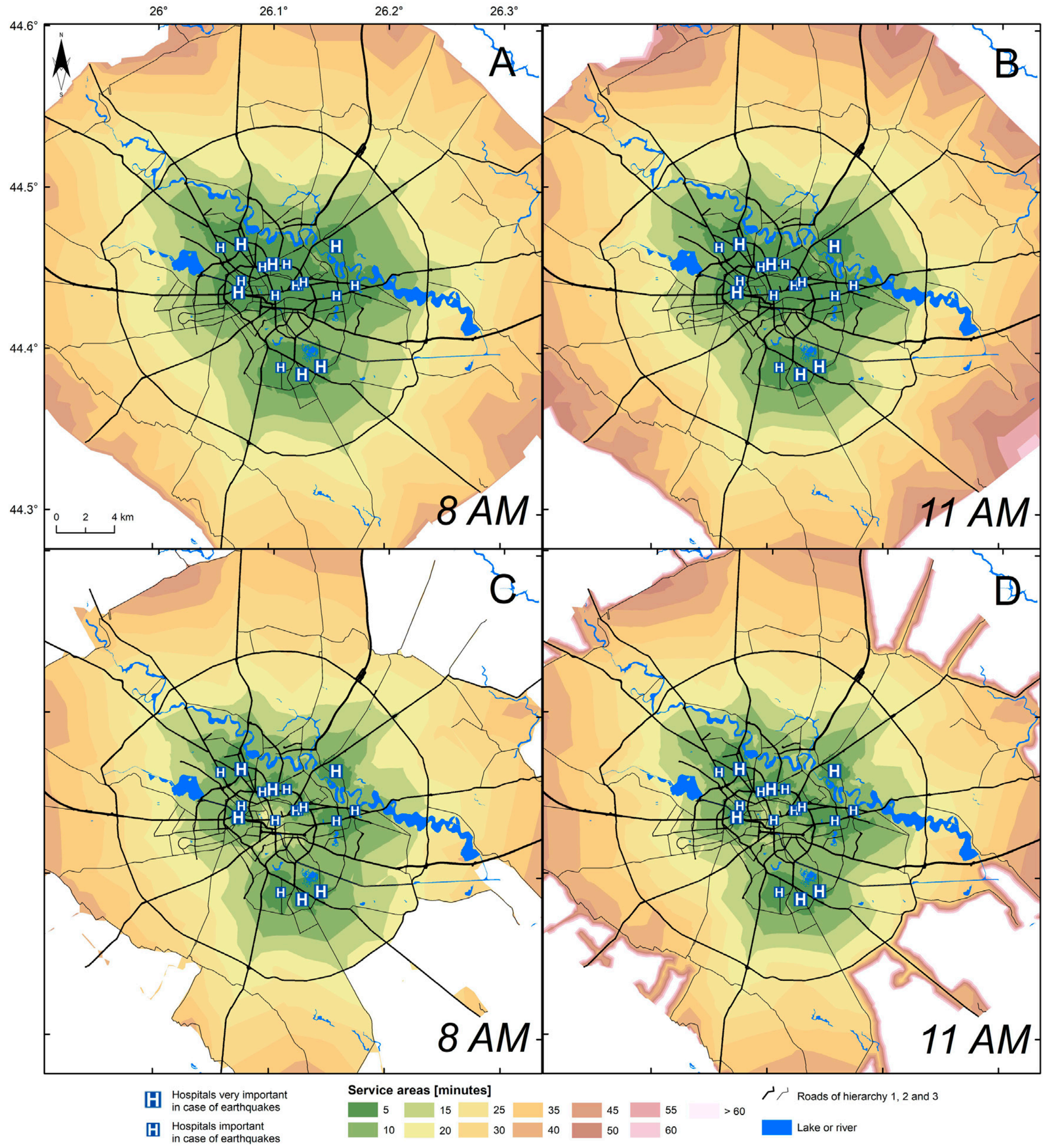

FIGURE 7 | Maps showing Service Area times for hospitals with very high and high importance in case of earthquakes, in pre-earthquake **(A,B)** and post-earthquake **(C,D)** conditions, for an earthquake occurring at 8 LT on a typical weekday.

How long would it take for ambulances and fire trucks to reach a location (or vice versa)?

Results of our methodology can show which areas are harder to reach by firefighters or ambulances—therefore having an increased potential of fire spreading or risk for emergency victims (when making correlations with graphs such as the golden-hour medicine time—Hekimoglu et al., 2013 or Goncharov, 1997).

Although our analysis can be performed for any time interval, we chose for this article the following representative scenarios, in order to reflect both the city's maximum risk compared to minimum:

- Earthquakes occurring at 2 (a.m.) LT and 8 (a.m.) LT, on a typical weekday;
- Time-dependent snapshot of the situation 3 h after the earthquake (at 5 and 11 LT)
- For the same time intervals, we computed travel times in no earthquake conditions, in order to facilitate comparison (**Figure 7**);
- Service Area analysis was performed with hierarchy enabled (given that preference for main roads is most possible also for

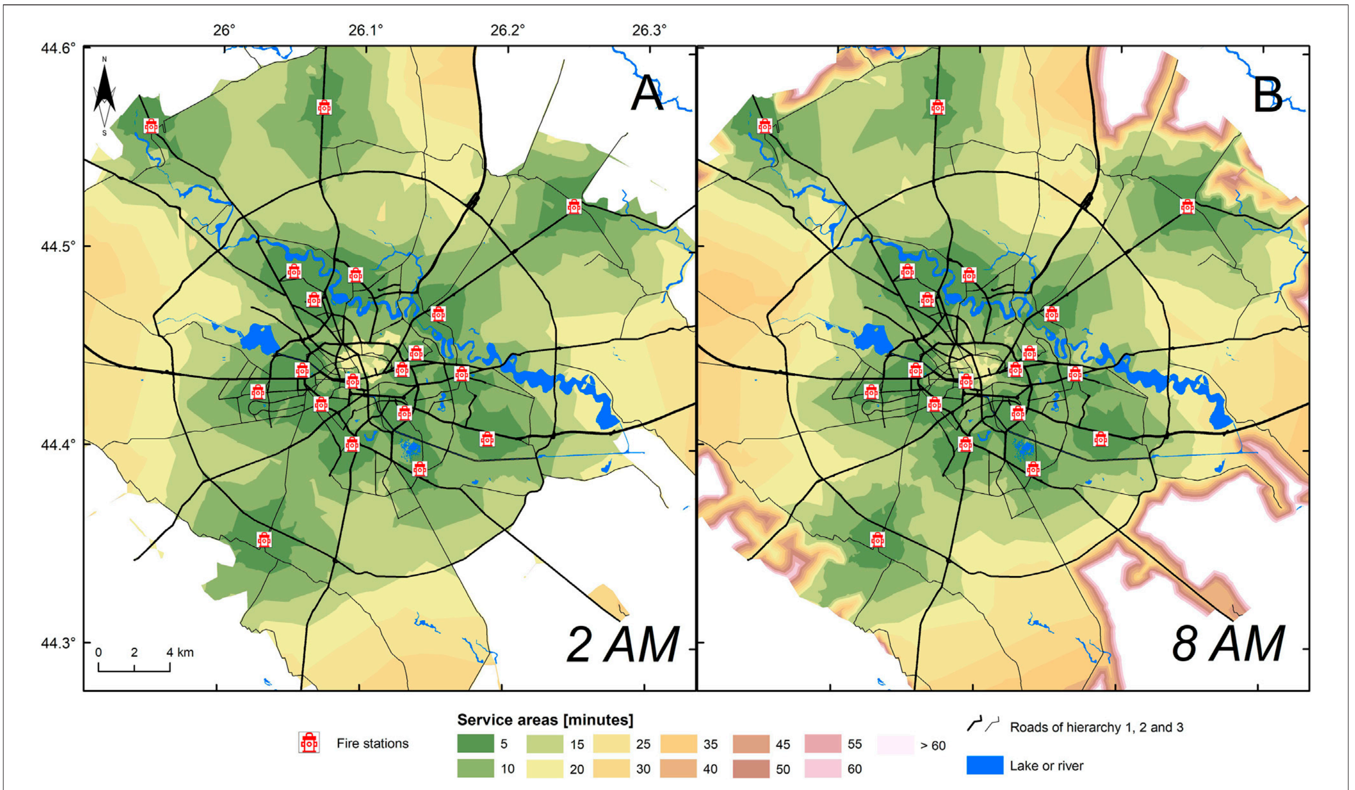

FIGURE 8 | Maps showing Service Area times for fire stations, in post-earthquake conditions, for an earthquake occurring at 2 LT **(A)** and at 8 LT **(B)** on a typical weekday.

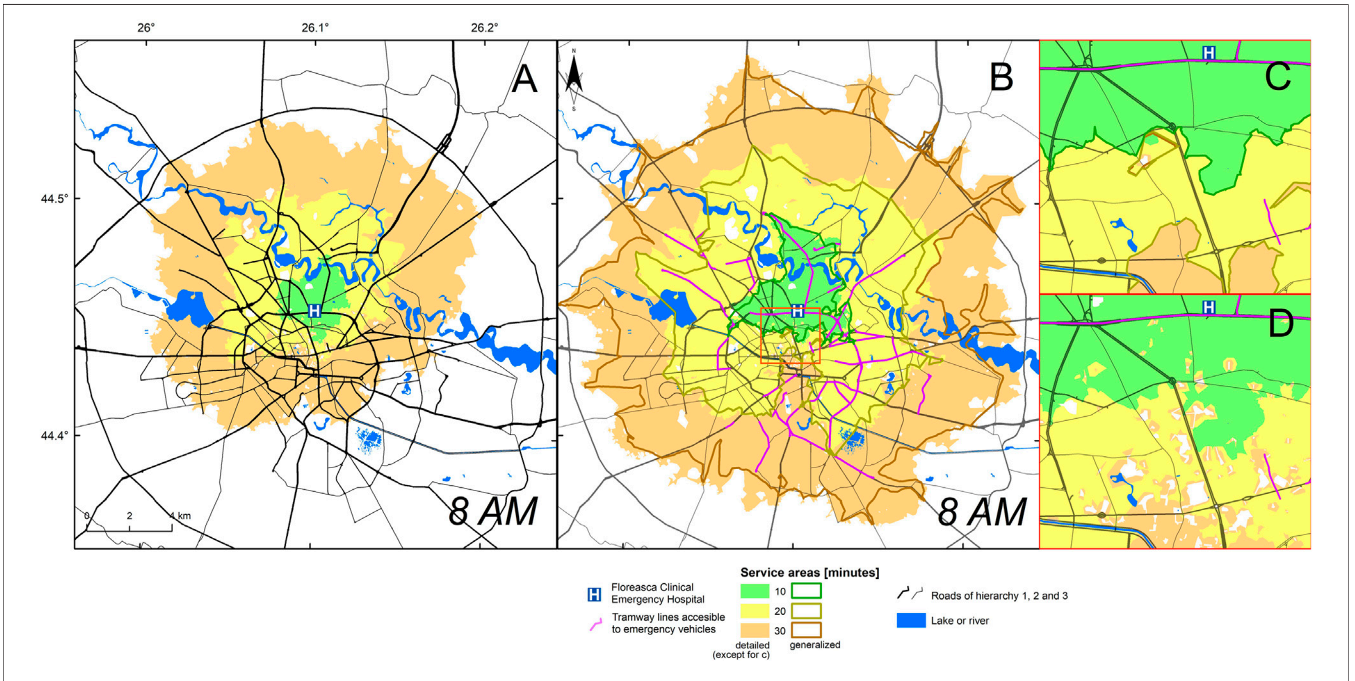

FIGURE 9 | Maps showing service areas for the Floreasca Clinical Emergency Hospital, in post-earthquake conditions, for an earthquake occurring at 8 LT on a typical weekday, without **(A)** and with **(B)** the asphalted specially delimited tramway lines. The zoom maps show service areas polygons created by ArcGIS with the generalized **(C)** and detailed **(D)** option.

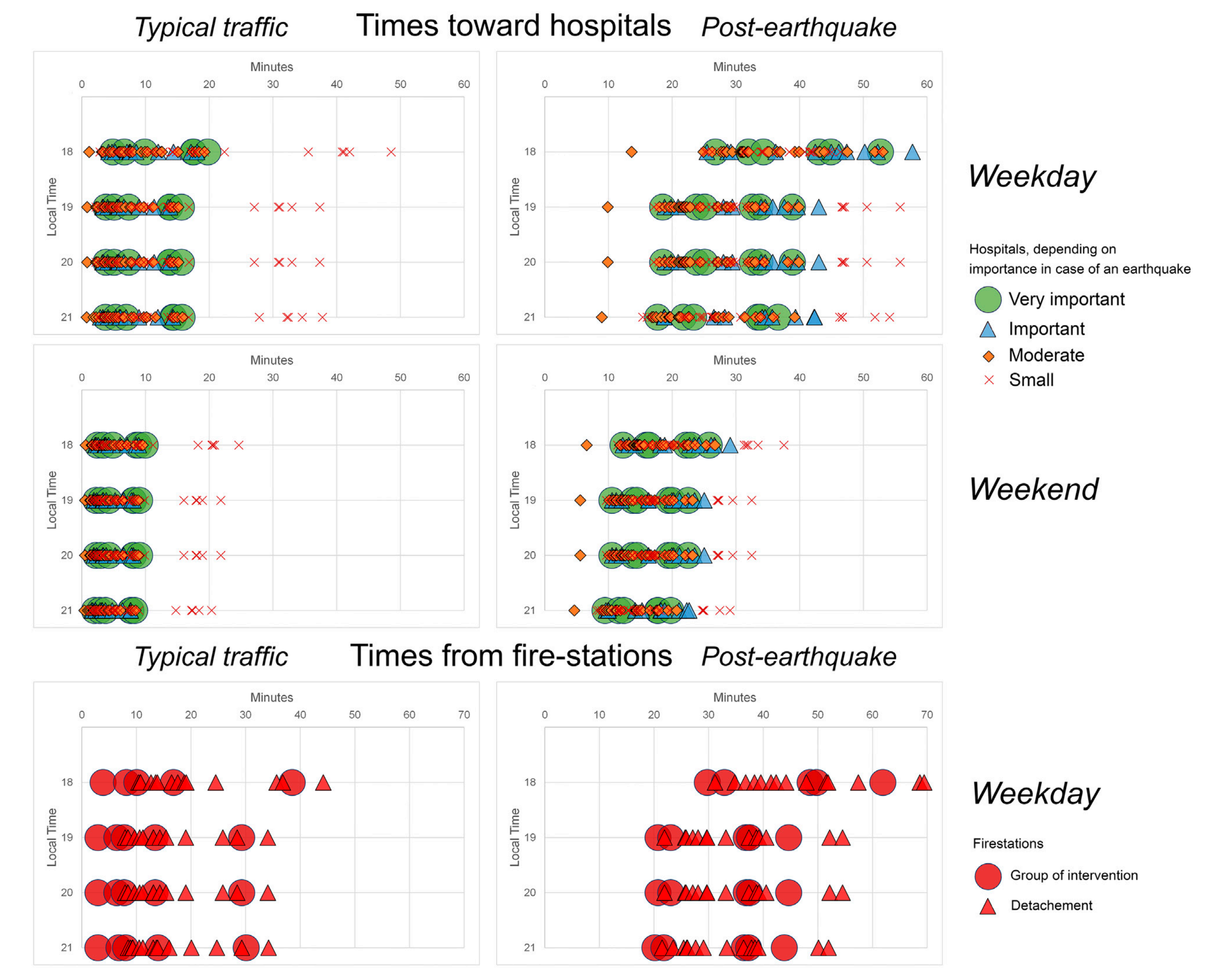

FIGURE 10 | Graphs showing the time between the Calea Victoriei 95-101 location and hospitals and fire stations, for typical traffic (at 18—21 LT on a typical weekday and weekend) and post-earthquake traffic, for an earthquake occurring at 18 LT

moderate or large-size emergency intervention vehicles), no one-way restrictions, generalized polygons, toward facilities for hospitals of very high and high importance in case of earthquakes (**Figure 7**) and away facilities for fire-stations (**Figure 8**).

In order to show the importance of safe routes for emergency intervention vehicles (such as the tramway line segments in Bucharest), we performed a Service Area analysis for the highly important emergency hospital Floreasca, located near such safe routes. **Figure 9** shows the time-travel differences between using and not using these safe routes, for the earthquake occurring at 8 LT described above.

As reflected by **Figure 9**, the generalization of Service Area polygons in ArcGIS smooths the shapes (and also improves the computational demands) but the results fail to show small road segments becoming not accessible due to building debris and sudden increases in traffic values. For decision makers, an additional layer such as the one in **Figure 6** should be overlayed.

Most vulnerable areas in case of an earthquake, due to limited connectivity, can be identified by service area analysis. Various emergency facilities and their characteristics can be considered (such as treatment capacity), but also considerations regarding second or third best available choices, as indicators of backup and resilience. Maps showing systemic resilience can be developed, using an index such as the one in Toma-Danila et al. (2020). In this study we however chose to present, in the context of time-dependent analysis, an example based on Closest Facility analysis and timeline graphs (**Figure 10**) for a highly representative area: Calea Victoriei, in front of the 95 and 101 adjacent buildings with SRC I, which were affected by the 1940 and 1977 earthquakes and which are located in the city center, near many other vulnerable

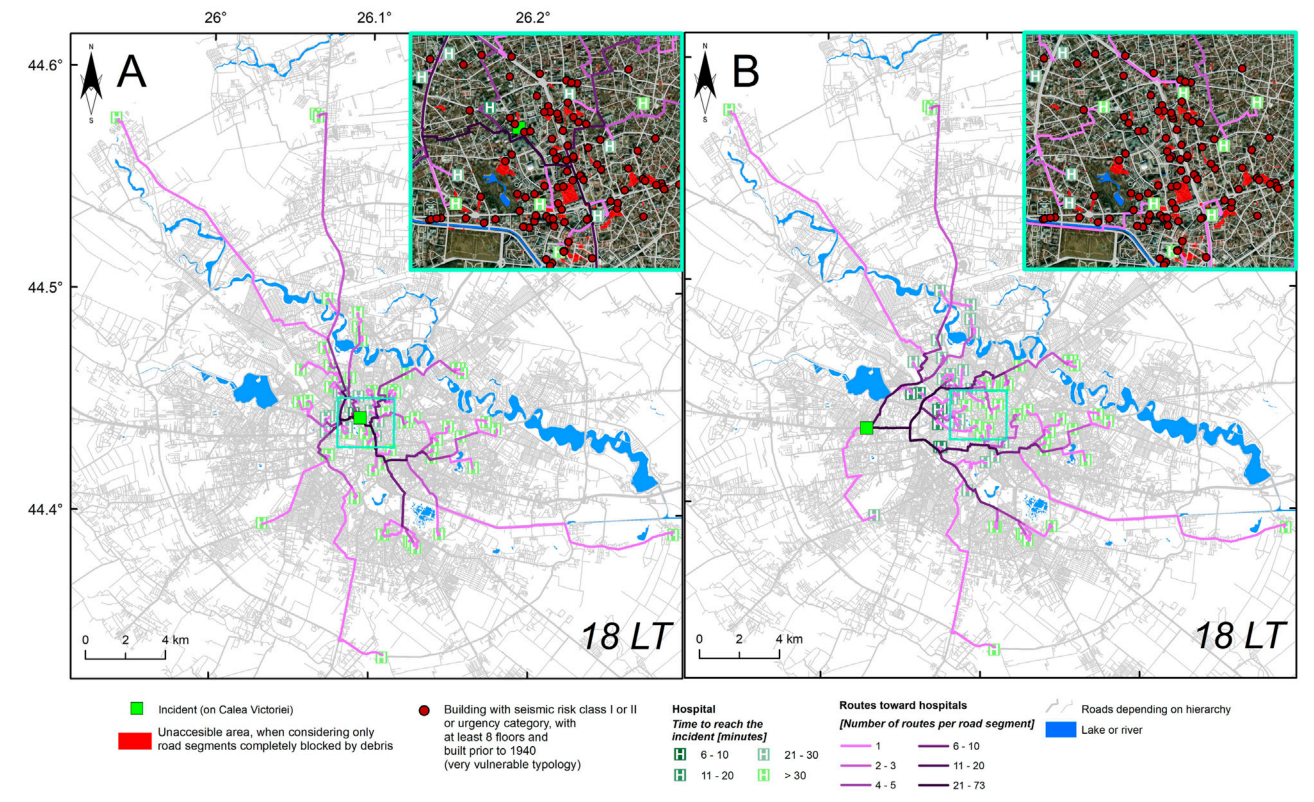

FIGURE 11 | Maps showing safest and fastest routes toward hospitals, for two representative locations: Calea Victoriei 95—101 **(A)** and Iuliu Maniu Bd. 55 **(B)**, in the case of an earthquake occurring at 18 LT on a typical weekday. Maps also show the number of roads overlapping per road segment.

buildings. Both the area and representative routes can be seen in **Figure 11**.

Which would be the most important roads in emergency situations?

For identifying which are the most transited road segments in order to provide the quickest access to facilities (we used in our analysis all hospitals), we recommend the following steps in ArcGIS:

- Perform Closest Facility Analysis on a greater than 1 number of facilities to find;
- Run the *identity* function, between road segments and results of the Closest Facility Analysis
- Perform a query to keep only common segments
- Run the *summary statistics* function in ArcGIS for counting how many overlapping segments exist
- Make a join between the road network and the resulted table to map the values.

For a demonstration, we considered for the analysis two representative locations as incident point: Calea Victoriei 95–101 (in the city center) and Iuliu Maniu Bd. 55 in the Militari neighbourhood, near the Veteranilor Market, an area far from hospitals but where a high-rise building collapsed during the 1977 earthquake and others are on the AMCCRS lists. The first location is near inaccessible areas, still our analysis shows that, for our worst-case scenario, routes are available to all hospitals. **Figure 11** shows routes critical (considering also hierarchy) for minimum access times to hospitals can be seen. A discrimination or weighting depending on hospital importance, showing also second-best routes and a graph comparison such as in **Figure 10** can be further performed. Some branches, with darker colors, are clear—indicating a route important for access to multiple hospitals. There are also similar routes between **Figures 11A,B**; for multiple locations, a count of multiple routes would be very useful.

This procedure could be also relevant for multiple routes calculated between affected buildings and closest hospitals or fire stations, as it was done in Toma-Danila et al. (2020).

Bridges, tunnels and passages are important structures which enable a fast connection, crossing or bypassing critical points. If these, due to direct damage or other incidents (such as accidents), would become unsafe, what would be the implications on travel times? By using route analysis, we tested what would happen in low traffic condition, without any other post-earthquake scaled costs, if the Constanta and Basarab passages would be closed (**Figure 12**). As mentioned earlier, these structures have a relatively high potential of disruption in case of an earthquake. It can be observed that minimal transit times increase greatly in the case of the Constanta passage (with more than 5 min and more than double the distance)—showing that this is a critical

FIGURE 12 | Maps showing the time between representative points, when connected by the Constanta Passage **(A,B)** and Basarab Passage **(E,F)** and not connected by these structures **(C,G)**, In no earthquake conditions, at 2 LT on a typical weekday. **(D)** shows the areas of the passages within Bucharest.

point. In the case of the Basarab passage, there are more than 2 min of extra time; also, multiple routes, slightly higher in times, are available given the greater density of roads. However, post-earthquake traffic and the first-hours chaos could greatly increase the times.

DISCUSSION

Figures in this paper are just a selection aimed to show the main capabilities of our framework; within the National Conception for Post-Earthquake Response, we will provide more detailed figures for multiple time intervals, enabling a practical use of this tool in decision making. Our results can also contribute to the development of systemic vulnerability functions reflecting for example the delay potential in case of various earthquakes or functions reflecting hospital resilience (for example, for various time windows and earthquake loss scenarios, a function reflecting the number of patients, considering travel times), with links to the work of Sun et al. (2021). These could be developed in future studies, although due to the complexity of the modeling and the multiple sources of uncertainty, as well as the continuously updating input data, we think that the scenario-based approach presented in this paper can be more suitable for emergency management planning and in near-real time situations. Various scenarios for decision-based risk mitigation measures can be tested using our framework: The impact of imposing of traffic restrictions and of opening or reopening of specific road segments, at different times after the earthquake. The analysis could also be expanded to other types of transportation networks such as railways, in relation with evaluations regarding the utility of earthquake early-warning systems, as explained in Minson et al. (2021). When using electric, pipeline, gas or water pipeline networks, an approach such as ours could integrate resilience frameworks such as Leandro et al. (2021).

In order to enable near-real time implementation, it would require to embed (preferably automatically) in a system using our framework:

- Real traffic data, from providers such as Waze or from monitored emergency vehicles;
- Continuous updates of affected areas and how many emergency vehicles and of which type they require (can be also taken by drones);
- Continuous updates regarding hospital number of patients.

For time-dependent and real-time data integration capabilities, additional challenges can arise:

- Real data, regarding affected buildings and infrastructure or traffic incidents, continuously updates, therefore new information must be easily integrated; this data can also refer to the evolution of rescue activities and need of additional forces on sites, results of rapid structural inspection, repair works and their evolution, emergency facilities lack of functionality etc.
- No data doesn't necessarily mean that the situation is good; in earthquake situations for example, the "doughnut effect" (Bossu et al., 2017) should be accounted for, otherwise less affected areas could be prioritized for intervention in the detriment of severely affected areas.
- Multiple sources of data need to be easily transferable in a network-modeling system; for example, in case of traffic data, different road datasets not joinable with between them (and a mistreating of from-to and to-from data) can lead to wrong travel times.
- Computational demands for complex network models could be extensive, therefore a selection of computational time-effective performance indicators needs to be performed.
- The impact of management actions (such as building instrumentation, mobile hospital deployment or establishment of dedicated emergency intervention routes) should be considered both in simulation and in real time.

What Could Be Improved Regarding Hospitals?

Some hospitals, due to their location close to affected areas but also due to treatment capacity and acknowledgment in the mental perception of citizens could be, in the first hours after an earthquake, much more crowded than others. This would be the case of the Floreasca and University Clinical Emergency Hospitals, which are both renowned institutions in emergency medicine and close to the city center. As **Figure 9** shows, Floreasca Hospital (but also disaggregated data of **Figure 7** for both hospitals) has a relatively good time coverage of all of Bucharest for the considered scenario, meaning that within an hour or two after the earthquake it could become overcrowded. Also, central locations such as Coltea Hospital would be highly busy—given the adjacency to the vulnerable city center and many hard-to-reach areas. In this area, the installation of a mobile hospital would be a good option and our type of analysis can and has served to the identification of reliable locations (Armas et al., 2020).

Given that in the western part of the city there are no hospitals with at least moderate importance capabilities in case of earthquakes (with higher reach time as shown by **Figure 7**), the need to build a hospital in this area is major, considering also the high seismic loss estimates shown in Toma-Danila and Armas (2017) and the multiple vulnerable buildings shown especially in the Militari neighborhood in **Figure 4**.

CONCLUSION

In the last years, multiple studies have started to analyze the direct and indirect effects of earthquakes on road networks, with a focus on the emergency intervention travel times between hospitals and affected areas. However, not many of them accounted for the time-dependent evolution of the situation, setting also premises for near real-time implementation. In this article we make steps forward, creating and testing a flexible framework which relies on already available and widely used GIS software (ArcGIS with Network Analyst extension). The framework links various relevant aspects reflected by real situations, such as traffic issues in post-earthquake situations, the impact of building debris on road networks but also characteristics of emergency facilities such as hospitals—important to consider as also reflected by the COVID-19 pandemic period. By using traffic profiles, scaled costs and restrictions to influence the typical traffic times we showed an easier yet satisfactory methodology of incorporating evolutionary traffic modelling and road blockages in the analysis.

As showed in this article, some of the outcomes of our framework, especially when implemented in near-real time, are that it:

- Plays an important role in post-earthquake traffic management, indicating roads that need to be accessible and areas where police intervention is needed to allow a decrease of travel times between affected areas and critical hospitals;
- Lets rescuers know which hospital they should send victims and on which route;
- Has a role in decision making, enabling the understanding of which hospitals to expand and where to place mobile hospitals not just in terms of adjacency to affected areas but also considering easy access to it.

Results will contribute to a more relevant National Conception for Post-Earthquake Response, indicating the actual risks due to high travel times in emergency situations and in reducing these risks through the need of seismic retrofitting (for residential buildings but also for hospitals and infrastructure elements), traffic management and increased capacities for critical hospitals or the construction of new facilities in specific areas (such as western Bucharest).

Given that the risk of Bucharest is significant and not easy to evaluate, also due to limited data available, we provide through this study also relevant GIS datasets regarding roads (based on OSM data), hospitals and fire stations. Also, through the version 2 of the Network-Risk toolbox (Toma-Danila, 2021a) we introduce a partially-automated and rapid methodology for the conversion of this data in ArcGIS format, which will facilitate the implementation of our analysis in many other case study areas.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories (Toma-Danila 2021a, b and c). The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

AUTHOR CONTRIBUTIONS

DT-D had the idea of the study and coordinated it, gathering also feedback from stakeholders interested in the outcomes of the study and creating all the figures. The analysis framework was defined by DT-D, DD'A, LS, and IA, while the modelling and software implementation was performed by DT-D and AT. DD'A, LS and IA provided important feedback on the state-of-the art and on the innovative potential of the study and considerably helped in structuring the document.

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The Seismic Early Warning System of Mexico (SASMEX): A Retrospective View and Future Challenges

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The earthquake early warning system of Mexico, SASMEX, has 30 years of uninterrupted and successful operation. During this time, the system recorded ~9,800 earthquakes and broadcast 111 alerts. Alerting was simplified recently, avoiding the emission of two types of alerts. Only earthquakes above a magnitude threshold, dependent on distance to the target city are alerted. SASMEX disseminates early warnings using dedicated receivers, public loudspeakers, multi-hazard radios, and participating TV and radio stations. It is estimated that ~25 million people receive alert messages from SASMEX. Cell-broadcasting messaging, necessary for the timely delivery of alerts, is not implemented by the local cellular phone operators. The addition of cell phone communication would increase the number of users benefitting from the system. SASMEX does not publish ground motion predictions at the time of issuing the alert. Instead, it distributes a map of peak ground acceleration in Mexico City ~1 minute after the arrival of strong motion, via electronic messaging. The accepted practice for the population in general is to evacuate at the sound of the alert. This is useful in schools and low-rise buildings, where people are generally drilled to evacuate rapidly. It is not effective in high-rise buildings and where large numbers of people concentrate. Finding protection and not trying to evacuate may be a better option, as it is recommended by other seismic early warning systems. The damaging 19 September 2017 earthquake underlined the difficulties of alerting earthquakes at close distances. Using a different sound of the alert or a countdown may be advisable, so people understand they have less time than normally assumed. There are few social studies on the use of the alert. It is suggested to conduct these studies to explore better ways to use and communicate the seismic alert, including automatic processes to shut down hazardous facilities.

Keywords: EEWS, SASMEX, Mexico, hazard reduction, alert dissemination

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INTRODUCTION

The Seismic Early Warning in Mexico (SASMEX) is a pioneer in the effort of warning the population of impending large earthquakes. The system began operations in August 1991 and in August 1993 it became the first seismic early warning system (EEWS) in the world to openly broadcast seismic alerts to the general population via subscribing radio and television stations (Espinosa-Aranda et al., 2009). The Center for Instrumentation and Seismic Recording, CIRES (Centro de Instrumentación y Registro Sísmico, in Spanish), is the non-profit organization that was made responsible by the government of Mexico City to develop, build, and install the system. Since its foundation, SASMEX

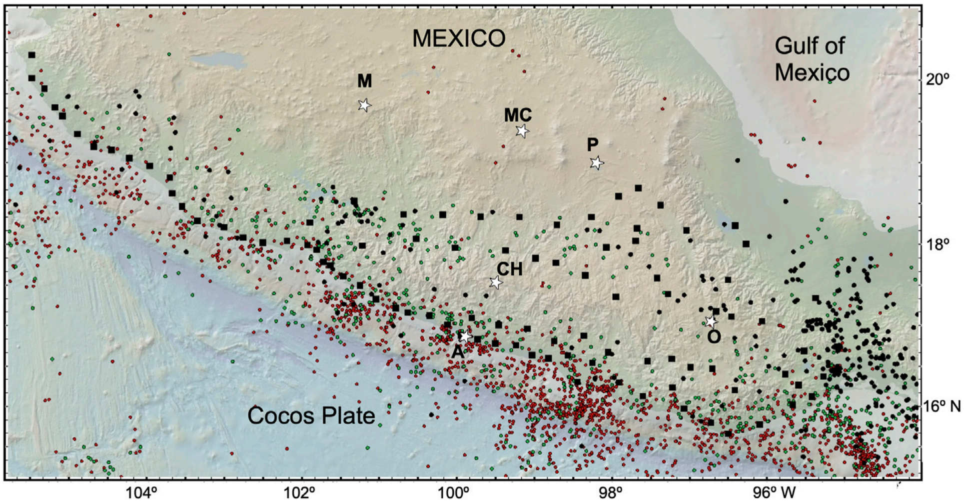

FIGURE 1 | Location of accelerographs of the EEWS in Mexico (black squares). White stars are the cities subscribed to SAMEX that broadcast alerts: A, Acapulco; Ch, Chilpancingo; M, Morelia; MC, Mexico City; O, Oaxaca; and P, Puebla. Earthquakes from the catalog of the Seismological Service of Mexico from 1 January 1970 to 31 December 2021: focal depths from 0 to 30 km (red dots), 30–70 km (green dots) and deeper than 70 km (black dots).

has screened ~9,800 earthquakes and has issued 111 alerts 8 (http://www.cires.org.mx/sasmex_historico_n.php). The system was one of the several risk reduction measures undertaken by the Mexican government after the disastrous earthquake of 19 September 1985. Originally, SASMEX was designed to warn only Mexico City of large earthquakes in the Guerrero seismic gap, immediately to the south of the city. This segment of the subduction zone has not experienced large earthquakes for many decades. It was assumed that seismic energy build-up in this region would generate eventually a large and damaging event (McCann et al., 1979; Singh et al., 1981).

EEW systems are the victim of a distance paradox. Cities are more prone to be damaged the closer they are to destructive earthquakes. However, the closer cities are to the epicenter, the less time there is to warn the population. In this respect, Mexico City represents a very advantageous scenario to operate an EEWS. The city is in an area of very high seismic activity and is frequently affected by the presence of large earthquakes. Since historical times, Mexico City has suffered extensive damage caused by earthquakes at distances of over 300 km (Suárez et al., 2020). The reason for this high seismic exposure is that the city was built on the soft clays of a lakebed drained over the past 500 years. Incoming seismic waves are highly amplified in the soft sediments, inducing large and long-lasting amplification of the ground, that are unusual for relatively distant earthquakes (*e.g.*, Bard et al., 1988; Kawase and Aki, 1989; Ordaz and Singh, 1992; Chávez-García and Bard, 1994; Wirgin and Bard, 1996; Reinoso and Ordaz, 1999).

The potential of a large earthquake in the Guerrero gap led to the construction of the Mexican EEWS, originally called SAS (Sistema de Alerta Sísmica) (Espinosa-Aranda et al., 2009; Cuéllar et al., 2014). It was estimated that the time elapsed between the detection of a large earthquake in the subduction zone and the arrival of the strong-motion seismic waves in Mexico City, would allow at least 60 s for the population to take protective actions. Thus, twelve stations were installed along the Guerrero subduction zone as the initial effort of the Mexican EEWS. During the first years of operation, it became clear that large earthquakes outside of the area covered by the initial system and felt strongly in Mexico City were not being properly alerted. To be effective, the system was expanded to be able to warn against earthquakes coming from other seismic sources, outside of the Guerrero gap. From the initial twelve stations, the system began an ambitious expansion in 2010 (Espinosa-Aranda et al., 2011).

Today, SASMEX has 97 stations distributed in southern Mexico that monitor not only the subduction zone but also the earthquakes that occur within the subducted slab of the Cocos plate, at depths between 50 and 180 km (**Figure 1**). These seismic events frequently cause damage to population centers in continental Mexico. Recent articles review the history, current distribution, and operational characteristics of SASMEX (*e.g.,* Espinosa-Aranda et al., 2009; Suárez et al., 2018).

After 30 years of operation, it is worthwhile to take a retrospective look and to assess the performance of SASMEX, and to reflect on future developments that could expand and serve better its purpose and mission, from both a technical and a social point of view. This paper makes a brief review of its development and achievements and proposes several avenues to improve its performance and social impact, not only in Mexico City but also in other cities in southern Mexico that have become part of the system.

THE STRUCTURE AND GROWTH OF SASMEX

In 30 years of uninterrupted operation, the system has been very successful. There is only one false alert issued since its inception.

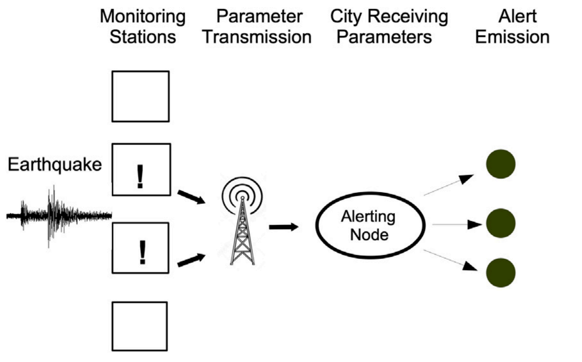

FIGURE 2 | Schematic operation of SASMEX. The dedicated accelerographs continuously monitor ground motion. When two adjoining stations exceed the pre-established thresholds of acceleration during an earthquake, the empirical parameters associated to moment magnitude are sent to central facilities at participating cities via radio links. These nodes then emit the alert to users using the various communication modes.

In the early development stage, when the system was still under testing, it was ordered by the local authorities for the system to go public. An alert was issued on 16 November 1993 when no earthquake occurred. Interestingly, many people in Mexico City consider this as the typical example of a false alert (Allen et al., 2018; Allen and Melgar, 2019). I consider that the worst-case scenario is when a large and damaging earthquake occurs, and no alert is broadcast; no such failure has been experienced by SASMEX in 30 years.

Today, besides Mexico City, five other cities in southern Mexico receive SASMEX seismic alerts: Acapulco, Chilpancingo, Morelia, Oaxaca, and Puebla (**Figure 1**). The 97 accelerographs that are exclusively designed and dedicated to SASMEX cover the Mexican subduction zone and the continental region of central Mexico, where earthquakes occur in the downgoing Cocos plates. In contrast with other early warning systems, SASMEX does not receive data from the National Seismological Service (SSN) or the other regional seismic networks in Mexico (*e.g.,* Kamigaichi et al., 2009; Given et al., 2018).

The Mexican seismic alerting system is based on a straightforward process. Three algorithms running in parallel at the sensing stations continuously monitor the strong motion data in three time intervals of the accelerograms, referenced to the arrival of the *P* and *S* waves: 2(*S-P*)*, S-P,* and in the first 3 seconds after the detection of the *P* wave. Essentially, the algorithms measure the logarithm of the peak ground acceleration and the cumulative acceleration. These parameters are calibrated empirically to a moment magnitude threshold (Cuellar et al., 2017a; Cuellar et al., 2017b; Cuellar et al., 2018). When the threshold estimated by any of the algorithms surpasses the established values at two adjoining stations, the parameters are sent to the central facilities in the participating cities to emit the alert (**Figure 2**). A distance versus magnitude criterion decides which cities should broadcast an alert, depending on their distance to the epicenter. In this respect the system is binary: it simply issues an acoustic tone warning the population of an impending large earthquake, screening earthquakes with magnitudes smaller than the threshold.

Unlike other EEW systems, SASMEX does not transmit accelerograms in real time to the central facilities that decide whether to alert or not. Each SASMEX station works independently and transmits via radio communication links only the parameters that are used to calibrate the magnitude threshold (Espinosa-Aranda et al., 2009; Cuellar et al., 2017a; Cuellar et al., 2017b; Cuellar et al., 2018; Suárez et al., 2018) (**Figure 2**). Hence, data transmission and the communication infrastructure are kept to a minimum and are simple and robust. This is important in a country where internet access to remote sites is faulty or inexistant. Central stations installed in the cities where the alert is issued receive these parametric data from the field stations and independently decide when to issue the alert.

DISSEMINATION OF THE ALERT MESSAGES

Dedicated Receivers

Initially, SASMEX broadcast alerts through 25 participating radio and television stations and 205 dedicated receivers built by CIRES. These instruments receive the seismic warning signal via radio links and activate built-in loudspeakers to disseminate the alert locally. However, the high capital cost and maintenance fees of the dedicated receivers severely limited the coverage and the number of people that received the alerts. Suárez et al. (2009) documented that only 76 schools out of 5,500 had a dedicated receiver in Mexico City. Considering that schools were the prime target for an EEWS in Mexico, this situation was unacceptable. The introduction in 2010 of ~90,000 multi-hazard radio receivers exponentially increased the number of people receiving the alerts. These radios are similar to the National Weather Radio of the National Oceanographic and Atmospheric Administration (NOAA) using the Specific Area Message Encoding (SAME). Today, all public elementary schools in Mexico City use these radios to receive the alert. Since 2015, the government of Mexico City decided to broadcast the alerts in ~12,600 loudspeakers distributed throughout the city. It is estimated that about 25 million people now receive the alerts issued by SASMEX.

Initially, the Mexico City government instructed CIRES, the parent organization responsible for SASMEX, to issue two types of alerts: preventive and public. Preventive alerts were broadcast only to the dedicated receivers for earthquakes with body wave magnitudes $5.0 < m_b < 6.0$. Alerts for earthquakes $m_b \geq 6.0$ were broadcast also by the participating radio and television stations as public alerts. Later, the government changed the magnitude ranges, requesting preventive alerts be issued for earthquakes $5.0 < m_b < 5.5$ and public for magnitudes greater than 5.5. This two-tiered system of alerts was confusing to the public and, predictably, SASMEX algorithms could not estimate magnitude in real time with this precision (Suárez et al., 2009). As a result, preventive alerts were issued frequently for events smaller than magnitude 5.0.

The technical innovations that multiplied the dissemination of preventive and public alerts made the distinction between them obsolete. SASMEX adopted a criterion of emitting a single alert based on a magnitude threshold criterion, calibrated as follows to a moment magnitude threshold and epicentral distance, D, to the target city: $Mw > 5.0$ for $D < 250$ km; $Mw > 5.5$ for $D < 350$ km; and $Mw > 6.0$ for $D \geq 350$ km. As a result of this change, fewer alerts are issued for small magnitude earthquakes, as was the case with the preventive alerts (Suárez et al., 2009).

Alert Messages *via* Cell Phones

SASMEX messages are not broadcast *via* cell phones, as in Japan and in *ShakeAlert* in California and the Pacific Northwest of the United States (Given et al., 2018). After the destructive 19 September 2017 earthquake, the Mexican government launched an experiment to issue warnings through a cell phone application called *911*. Subscribers were able to sign up and download the application freely. The experiment was predictably unsuccessful because the alerts were sent via regular messaging service without prioritizing their delivery. The number of subscribers increased rapidly and the delays in receiving the alert were often in the order of tens of seconds, making the system unusable. The government suspended the application after a few months.

Cell-broadcast messaging for cell phones is not available in Mexico because the local operators do not offer this service. Negotiations are underway between the government and cell phone operators to collaborate with SASMEX. In contrast, in Japan several cellular phone companies started to transmit EEW messages in 2009 (Kamigaichi et al., 2009). The availability of this service in Mexico would broaden the number of users that receive the alert in a timely manner and enhance the benefits of the EEWS. However, the large availability of cell phones and the corresponding broad distribution of the alert will underline the need to establish clear policies and protocols for the population, depending on their local circumstances.

PREDICTION OF GROUND MOTION IN REAL TIME

t has been discussed in recent years, whether SASMEX should follow other seismic early warning systems and predict the expected ground motion at the target cities for the earthquakes alerted. Some members of the scientific community argue that this is an important drawback and that SASMEX should begin to publish ground motion predictions simultaneously to the broadcast of alerts. Other voices, like this author, prefer to maintain a simple and straightforward manner of issuing alerts, without publishing predicted accelerations that potentially may confuse users, if these notices are not properly conveyed and disseminated. A reliable prediction of ground motion issued at the same time as the alert needs an accurate location and magnitude estimate within a few seconds after the origin time. The recent experience of the 2019 Ridgecrest, California earthquake highlights the difficulties to estimate ground motion in real time, even with a very dense seismic network as the one used by *ShakeAlert* (Chung et al., 2020).

This is particularly important considering the dramatic variability of seismic soil response in Mexico City to incoming seismic waves. Sites located in the central part of the city, sitting on the soft clays of the now dried-up lake, experience much larger intensities and durations of seismic motion than other sites located in what used to be the shore of the lake or the highlands (e.g., Reinoso and Ordaz, 1999). Singh et al. (1981) showed that spectral ratios on lakebed sites have relative amplifications that vary between 8 and 56 times. Seismic response differences between the lake and the highlands may represent variations of three to four units in the modified Mercalli intensity. Thus, authorities and users of the alert would need to know precisely where they are in the city, from a geotechnical point of view, to know what seismic intensity to expect a few seconds before the arrival of the strong motion.

Besides these considerations, there are two main reasons why SASMEX does not publish predictions of the intensity of seismic motion. As explained before, SASMEX does not calculate magnitudes and bases the emission of alerts on a magnitude threshold. The accurate estimation of magnitude would require a denser sensor network than currently available and to radically modify the architecture of SASMEX. More importantly, the civil protection authorities responsible for SASMEX have never requested and do not see the need for the prediction of expected ground motion, issued in real time at the time of the alert. Once a seismic alert is received by the authorities, several actions are put immediately in motion, instructing the institutions responsible to attend emergencies to be on guard and ready to act.

Instead of predicting ground acceleration in real time, the authorities requested that CIRES report the observed peak ground accelerations within a few seconds after the arrival of the strong motion waves. CIRES also runs the strong motion seismic network in Mexico City called RACM (Red Acelerográfica de la Ciudad de México). When an alert is issued, SASMEX puts the strong motion network on alert, and its stations report the peak ground acceleration at several key sites in the city. The measured peak ground acceleration values in Mexico City are published via *WhatsApp* and *Telegram* within the next minute after the arrival of the strong ground motion (**Figure 3**). In the recent 23 June 2020 earthquake (*Mw* 7.1) in southern Mexico, the report of measured peak ground accelerations was disseminated by CIRES 1 minute after the arrival of the *S* waves in Mexico City (Suárez et al., 2021). Thus, rather than providing authorities with maps of predicted ground motion, the integrated early warning system and the strong motion stations provide the authorities measured and reliable peak ground acceleration data with which to plan civil protection measures and rescue missions, within a few seconds after the strong motion is felt in the city (**Figure 3**).

The electronic messages showing the locations and value of recorded peak accelerations are sent to federal and local civil protection officials and to members of the scientific and engineering community. It is being considered to make these messages available to a broader constituency. Also, CIRES is evaluating how to calculate the duration of the strong shaking and to publish an additional map with this estimate in parallel to the peak accelerations report. Duration of strong shaking is an important parameter in Mexico City to rapidly assess potential damage in buildings after an earthquake. This is due to the very long

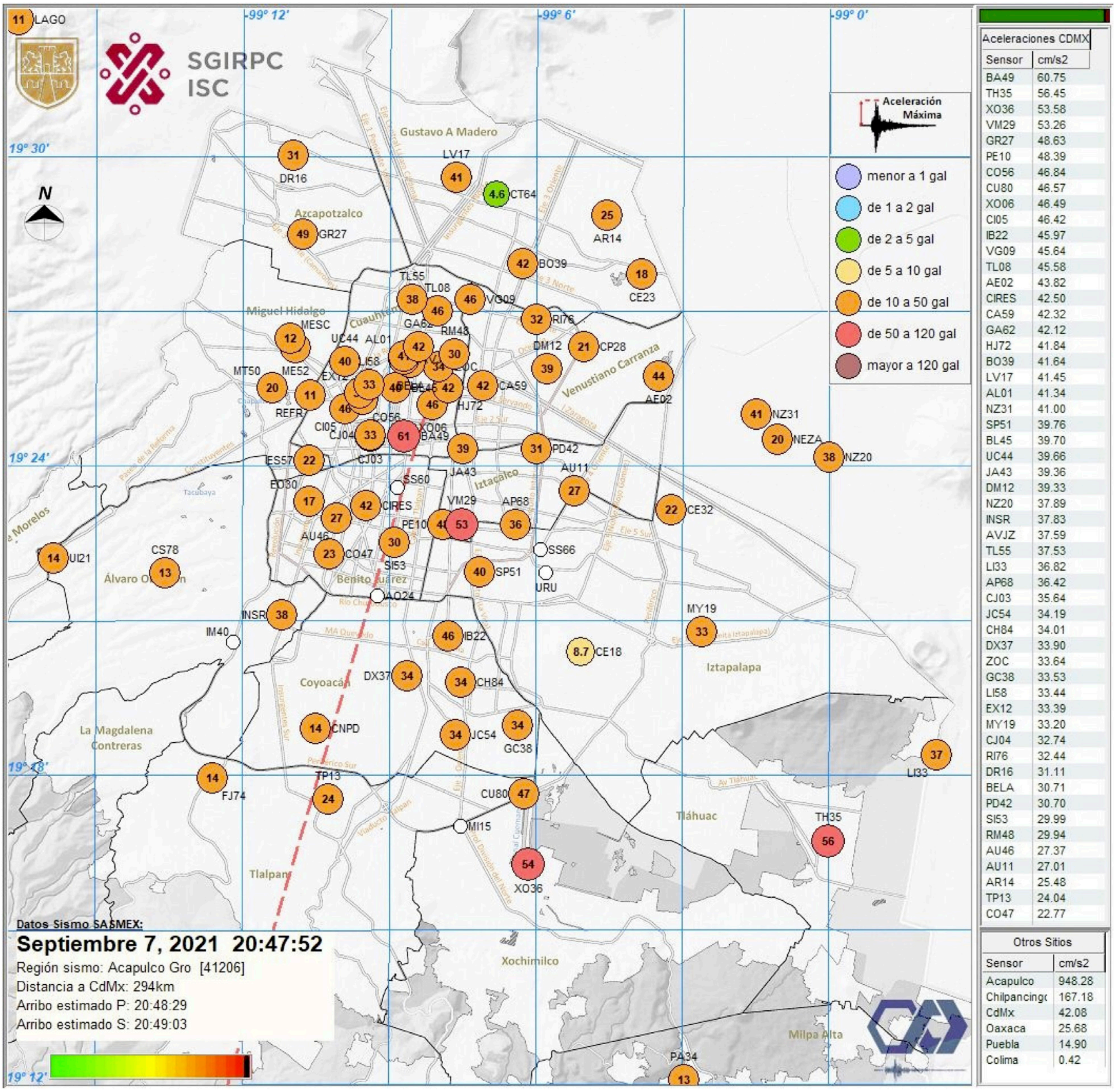

FIGURE 3 | Example of map sent *via* WhatsApp, Telegram, and internet messaging showing the observed peak ground acceleration in stations of the strong motion network of Mexico City for the 7 September 2021 Acapulco earthquake (Mw 7.2). These maps are sent to authorized users about 1 minute after the arrival of the strong ground motion in Mexico.

duration of high accelerations observed in the soft soils of Mexico City that have shown to damage buildings due to the repeated shaking of the structure (e.g., Zeevart, 1964; Meli et al., 1985).

REACTING TO THE ALERT: PROTOCOLS AND GUIDELINES

The unwritten instruction, and now common practice in Mexico, is for everyone to evacuate immediately at the sound of the seismic alert. Schools regularly conduct drills to vacate the premises on clearly marked evacuation paths, and the students are directed by designated civil protection personnel to pre-established meeting points. A similar practice is followed in government buildings and many private institutions. The practice to evacuate stems from the tragic memory of children who, during the 1985 earthquake, perished under the roof of their schools. Furthermore, schools in Mexico are normally low-rise buildings, two or three stories high. Considering that in Mexico City the time between the sound of a seismic alert and the arrival of the strong ground motion is at least 50 s for subduction earthquakes, this practice of evacuating low rise buildings may be a sound measure.

In contrast, it is difficult to conduct a full evacuation in this time span in buildings higher than about two or three floors, even when drills are conducted routinely. Evacuation times depend, among other factors, on the number of people in the building, the width and number of the emergency staircases and on the level of training of both the people in the building and the designated leaders of the evacuation (*e.g.,* Pauls, 1987). The time needed to evacuate buildings safely has been completely overlooked by the civil protection authorities. Thus, in the case of high-rise buildings, evacuation at the sound of an alert may not be always the best option. In contrast, *ShakeAlert* encourages the population to Drop, Cover and Hold-On (DCHO) until the strong shaking passed (McBride et al., 2021). Although warning times for earthquakes in the Cascadia subduction zone may be 50–80 s (McGuire et al., 2021), this practice is advisable due to the proximity of the seismic sources to the target population centers in California, where warning times for *ShakeAlert* range from a few seconds to no more than 15 s. Clearly, evacuation with these short warning times is not a plausible option in most cases. Moreover, a study of the Hayward Fault earthquake in California suggests that DCHO could prevent some the estimated nonfatal injuries (Porter et al., 2018; Sutton et al., 2020).

Perhaps the more important pending assignment for SASMEX is the establishment of procedures and protocols that are adequate for different institutional requirements, building types and locations, that instruct the public how to react in the case of an earthquake. After 30 years of SASMEX operations, authorities have not established specific guidelines and protocols on how different population sectors or institutions should react to a seismic alert. Arjonilla (1998), a sociologist who is an expert in public safety, was critical of the way the Mexican seismic alert system was being deployed without considering the potential users. Arjonilla (1998) considered the EEWS as an important tool to save lives and injuries. However, she argued that its implementation should be accompanied by ¨solid planning and preparation on the part of the community¨. Unfortunately, this advice is yet to be followed.

In the statutes of Mexico City describing the requirements to elaborate internal civil protection programs in residential dwellings, the only requirement is that buildings higher than 30 m or with a built area of more than 6.000 m^2, should install EEWS receivers approved by the government (TR-SGIRPC-PIPC-VMCH-004-2019TR-SGIRPC-PIPC-VMCH-004-2019). In the case of commercial and public facilities, the guidelines indicate that a seismic alerting system should be included in the common areas of commercial malls, buildings that in case of structural failure may constitute a significant danger, buildings that are essential during emergencies such as hospitals, schools, transportation centers, police, firefighter stations, and similar critical facilities (TR-SGIRPC-PIPC-EST-002-2019TR-SGIRPC-PIPC-EST-002-2019). The same norm also requires that buildings that host more than 250 people, such as churches, sports facilities, and any other establishment hosting massive public shows, should also have a seismic alerting system. The norms described here are only for Mexico City, the federal civil protection authorities have not issued any regulation or norm regarding the use or emission of earthquake seismic alerts.

Although not explicitly stated in the norms, the underlying assumption is that people would evacuate the premises at the sound of the seismic alert. This begs the question: Is it possible to evacuate a stadium, a movie theater, or a church in 60 s? Very likely, not. Thus, these general guidelines are neither helpful nor practical. Hospitals, for example, should have specific protocols and trained personnel to react to an alert, tailored to their specific needs. Surgeons should know beforehand how to react to a seismic alert before or during medical procedures, as well as the technicians responsible for support equipment. The procedures and actions to take during a seismic alert should be included in their civil protection manuals and protocols; the same may be said about facilities housing police, firefighters, or paramedics, for example.

The guidelines issued by UNISIDR (United Nations International Strategy for Disaster Reduction) indicate as a key element in early warning systems, the importance that the population are fully aware of the usefulness of the alert and the knowledge on what to do once the warning is issued. Cochran and Husker (2019) stress the public must be fully aware of what actions they should take when an alert is received. Also, the use of SASMEX should be considered not only to emit an audible sound to warn the population, but to put in place also automatic processes to close pipelines with flammable materials or to stop the subway or other massive transport system. The establishment of specific protocols may help to save more lives in the case of future major earthquakes. The main emphasis in the development of EEWS everywhere has been to improve the scientific and technical aspects of the system and worry about the societal uses and benefits afterwards. SASMEX has not been alien to this and 30 years after its creation clear social guidelines continue to be missing. In contrast, before investing in a nationwide EEWS, New Zealand first conducted a survey to understand whether the public considered an EEWS useful and acceptable, asking also when early seismic warnings should be communicated (Becker et al., 2020).

The pending task for civil protection authorities in Mexico, at both the local and federal level, is to focus on establishing norms that focus on the best protective actions to recommend to the users of the alerts issued by SASMEX.

THE CHALLENGE OF NEARBY EARTHQUAKES

The original mission of SASMEX to monitor subduction zone earthquakes conveyed the idea that warning times available in Mexico City were at least 50 s. Thus, the algorithms were designed

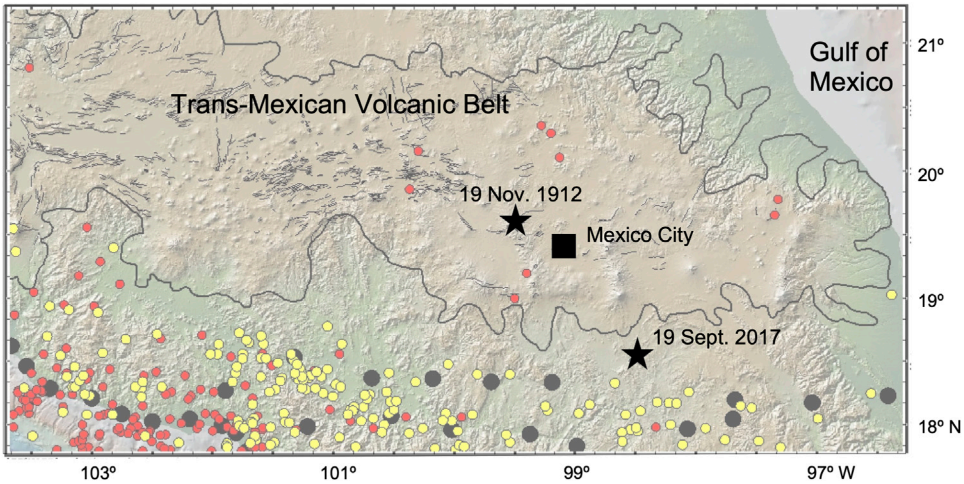

FIGURE 4 | Location of the 19 September 2017 (*Mw* 7.1) and 19 November 1912 (*Mw* 6.9) earthquakes relative to SASMEX accelerographs (solid black circles) and Mexico City (black square) from the same catalog and period as **Figure 1**. The yellow dots represent in-slab earthquakes and red dots are events shallower than 30 km. The black solid line represents the boundary of the Trans-Mexican Volcanic Belt, and the short black lines in it are mapped faults. The 1912 earthquake took place in one of these crustal faults.

to wait for the arrival of the *S* wave to estimate the magnitude threshold. It was obvious that earthquakes occurring inland, within the subducted slab, would offer a shorter warning time than subduction events. However, the earthquake of 19 September 2017 (*Mw* 7.1) was a shocking wake-up call on the challenges presented by earthquakes that occur close to Mexico City. This destructive earthquake was located ~100 km to the south of the city, at a hypocentral depth of 55 km. The closest SASMEX accelerographs were located above the hypocenter at approximately the same distance as the epicentral distance to Mexico City (**Figure 4**).

As a result of this geometry, the seismic alert was heard in Mexico City at the same time or a few seconds after the arrival of the strong seismic shaking. The reason was the location of the earthquake near the city and that the algorithm at the time triggered on the accelerations recorded in the *S-P* time (Cuellar et al., 2017b). The newly developed algorithm that triggers on the first 3 s of the *P* wave (Cuellar et al., 2018) was being tested and not installed yet in SASMEX sensing stations. However, had it been installed, the 3 s algorithm would have given no more than 10 s of warning in some parts of the city. Today, this faster algorithm is deployed in all inland SASMEX stations. Admittedly, estimating magnitude using only the first 3 s of the *P* wave is difficult (Colombelli et al., 2012; Colombelli et al., 2014). However, the algorithm now used in inland station can predict magnitude thresholds.

Unfortunately, in its 26 years of continuous operation, SASMEX was unable to give advance notice to the public for the only earthquake that resulted in substantial damage and loss of life in Mexico City. Santos-Reyes (2019) conducted a careful statistical analysis of the public reaction to this short warning times. His results show that the confidence in SASMEX decreased dramatically after the 19 September 1985 earthquake.

This experience showed that the network of SASMEX accelerographs covering these deep intraplate earthquakes needs to be densified. However, it also made clear that the idea of monitoring crustal earthquakes, as has been frequently discussed, presents serious challenges. CIRES has presented the government with several proposals to include coverage for these crustal earthquakes that take place in the Trans Mexican Volcanic Belt. The Acambay event (*Mw* 6.9) that took place on 19 November 1912, 80 km from Mexico City, is given as an example for the need to instrument this region (**Figure 4**). However, the future installation of these new SASMEX accelerographs should be accompanied by a careful consideration of how to broadcast the alert. It cannot be done in a business-as-usual manner as if these earthquakes were in the subduction zone. Furthermore, to have a timely alert of a few seconds in Mexico City, the number of accelerographs should be much denser than it is now in the south.

The public is used to periods of between 50 and 130 s to evacuate their buildings; this is certainly not the case for nearby events. One option is that earthquakes with warning times in Mexico City of less than 20 s, for example, have a warning signal with a different sound than subduction earthquakes. This would make the population aware that the time before the arrival of strong shaking is shorter than usual. A second option would be to introduce a count-down in the warning signal. In this manner, the public would know exactly how much time they have and be prepared. The results of the study by (Santos-Reyes, 2019) of SASMEX perceived performance during the two earthquakes of September 2017, indicates the importance of informing the public of the time between the alert and the initiation strong shaking. This second option has been discussed with the local civil protection authorities and it is agreed that it has *pros* and *cons* to it. In any case, the public must be massively educated to these innovations in disseminating the alert.

Whatever mechanism is chosen to differentiate seismic alert signals from earthquakes close to the city, the practice of automatic evacuation at the sound of the buzz is not always the more adequate response. In these cases, where the time of opportunity to evacuate buildings is very short, even for low-rise buildings like the primary schools, a practice like the DCHO used by *ShakeAlert* is probably the best option. School children in Japan are well drilled to duck under their work benches at school to protect their heads. The population should be well trained and prepared to act depending on their circumstances, the type of earthquake, and the resulting available warning time. This requires a well-coordinated, effective, and universal educational program and clearly established procedures and protocols that instruct people on how to react.

CONCLUSIONS

Undoubtedly, SASMEX has been very successful tool in the 30 years of continuous operations. It has developed instrumentation and algorithms adapted to the local infrastructure and technical capabilities. Once it started operations, after the initial development phase, it has successfully identified all large earthquakes in the area covered by the network and issued the corresponding seismic alert. Outside of the initial stages of testing, SASMEX has issued no false alerts. The system has expanded the emission of the alert to other five cities in Mexico, and it is rapidly becoming a nationwide tool for civil protection at the national level. It is fair to say that the public trusts the system, although studies in this respect are sadly lacking. However, proof of this trust is that people react to the sound of the alert and evacuate.

Unfortunately, in the case of the only earthquake that caused severe damage and loss of life in Mexico City, SASMEX was unable to provide sufficient time to warn the population of the approaching strong seismic shaking. The close distance to the epicenter and the ensuing brief warning time, stressed the importance of considering other ways of broadcasting the alert signals for earthquakes that due to the short epicentral distance, offer little time for the population to take protective measures. Although many news media reported the reasons of the short warning times for the 19 September 2017 earthquake, public confidence in the system decreased (Santos-Reyes, 2019).

The elimination of broadcasting public and preventive alerts, based on a rigorous measure of magnitude, which the algorithms were unable to distinguish, has decreased the number of alerts issued and the public is accustomed to receiving an alert whenever an earthquake is felt. This prevents the ¨crying wolf¨ syndrome that could eventually lead to loss of credibility of the alerting system (Reddy, 2020). The practice instituted since the advent of SASMEX for the automatic evacuation of buildings should be reconsidered and recommended only where there is sufficient time to do so. In high rise buildings and other facilities that are difficult to fully evacuate safely, even with the long lead times allowed by subduction earthquakes in Mexico City, should be convinced of adopting the DCHO practice that is the recommended behavior in the alerting systems of Japan and the United States.

There are few sociological studies on the optimal reaction and use of the alert by the public. These studies conducted by specialists in disaster prevention will help to determine the best course of action for different segments of the population and type of institution. The guidelines offered today by the authorities are very general and not conducive to best use of SASMEX. This is an important pending task since the initial stages of its implementation. These studies should consider guidelines for specific users, particularly those that are crucial after disastrous events, like hospitals, police, paramedics, and other type of personnel that are crucial in the immediate response to disasters. Studies of people´s reaction in other EEWS are examples that should serve to make SASMEX more people oriented based on specific and useful recommendations (e.g., Dunn et al., 2016; Nakayachi et al., 2019).

In addition, it is yet to be explored what actions should be taken that go beyond the emission of an audible tone. The automatic closing of gas lines, stoppage of public transportation, manage elevators in high rise buildings, controlling production lines and other actions that may be taken automatically to protect the population. There are many avenues to explore in order to make a more intense use of the seismic alert in Mexico that go beyond the knee-jerk reaction of escaping from buildings (Santos-Reyes and Gouzeva, 2020). From a seismological and engineering point of view, SASMEX has proved itself to be a reliable and robust system. The task ahead should concentrate in putting the population at the center of the discussion, exploring the best options to react and to implement norms and regulations that are conducive to saving lives and preventing injuries.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Object-Oriented Mapping as a Tool for the Assessment of Landslide Hazard in Higly Urbanized Areas

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The assessment and mitigation of landslide risk affecting hillslopes in highly urbanized and infrastructured environments are often problematic due to the inadequacy of the traditional approach based on landslide inventories and the absence of a shared language between the different scientific-technical operators (geologists, engineers, architects, environmentalists, economists, jurists) and recurrent understanding problems with policymakers, stakeholders, and property owners. Therefore, innovative technologies and working procedures are required to address these problems. In this context, the European INSPIRE Directive and the Italian national Catalog of Territorial Data with the related Geo-Topographic DB provide positive responses in terms of data standardization and transdisciplinary interoperability. On the other hand, the application of the object-oriented geomorphological mapping of landslides and, even more, the recently proposed Landslide Object-Oriented Model (LOOM) make it possible to develop a more thorough approach to assess the spatial and temporal relationships between landslides and affected slopes. Following the above perspective, the InterUniversity Research Center for Prevision and Prevention of Great Risks (C.U.G.RI.) produced the LOOM-based "eventory" of landslides over a sector of the Tyrrhenian coastal belt, northwest of Salerno city, in the framework of a multi-disciplinary investigation project launched by the Campania Regional Administration to assess the landslide risk. The quantitative assessment of the geomorphological expert-judgment procedures has been carried out exploiting morphometric indexes: the Topographic Position Index (TPI) for automatic slope features recognition, and the Slope-Area plots for surficial process domains. Furthermore, the application of the INSPIRE, and related Italian National Geo-Topographic DB standards allowed transdisciplinary interaction between scientists, technicians, and managers. Such proposal can support the risk management procedure, adding in the Value Judgement and Risk Tolerance Criteria simplicity and effective interoperability in trans-disciplinary frameworks.

Keywords: inventory map, object-oriented mapping model, transdisciplinary interoperability, european inspire directive, geo-topographic DB, landslide hazard assessment, eventory, loom

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1 INTRODUCTION

Since the early 1980s, quantitative methods and procedures have been increasingly applied to assessing landslide risk of single slopes within broad areas in the perspective of land planning and management (Varnes and IAEG, 1984; Whitman, 1984; Einstein, 1988; Fell, 1994; Cruden and Fell, 1997; Australian Geomechanics Society, 2000; Hartford and Baecher, 2004; Lee and Jones, 2004; Fell et al., 2005; Hungr et al., 2005; Canuti and Sassa, 2008; Corominas et al., 2014).

According to Fell et al. (2005), Fell et al. (2008), a quantitative assessment of landslide risk includes several outcomes such as 1) systematic analysis of the landslides characteristics, including their travel distance and velocity, frequency of reactivation phases, temporal-spatial distribution, vulnerability, and value of elements at risk; 2) applications to situations that are not amenable to conventional deterministic; 3) criteria used to determine the areas where the building is suitable; 4) prioritization of remedial works, and potentially setting of risk-based standards for appropriate designs; 5) regional governmental planning considering landslide risk management principles, in terms they can relate to other hazards. **Figure 1** summarizes the framework for landslide risk management taken from Fell et al. (2005).

In any case, a reliable quantitative approach to landslide risk assessment requires appropriate working procedures and technologies that may allow easier interaction among different disciplines and interoperability between different geographic information systems. In this perspective, the object-oriented inventory mapping of landslides, represented as spatial entities (objects) with a precise identity and persistence character (Egenhofer and Frank, 1987; Worboys et al., 1990; Worboys, 1994; Bian, 2007; Anders et al., 2009; Lahousse et al., 2011; Verhangen and Drăguţ, 2011; Blaschke et al., 2014; Guida

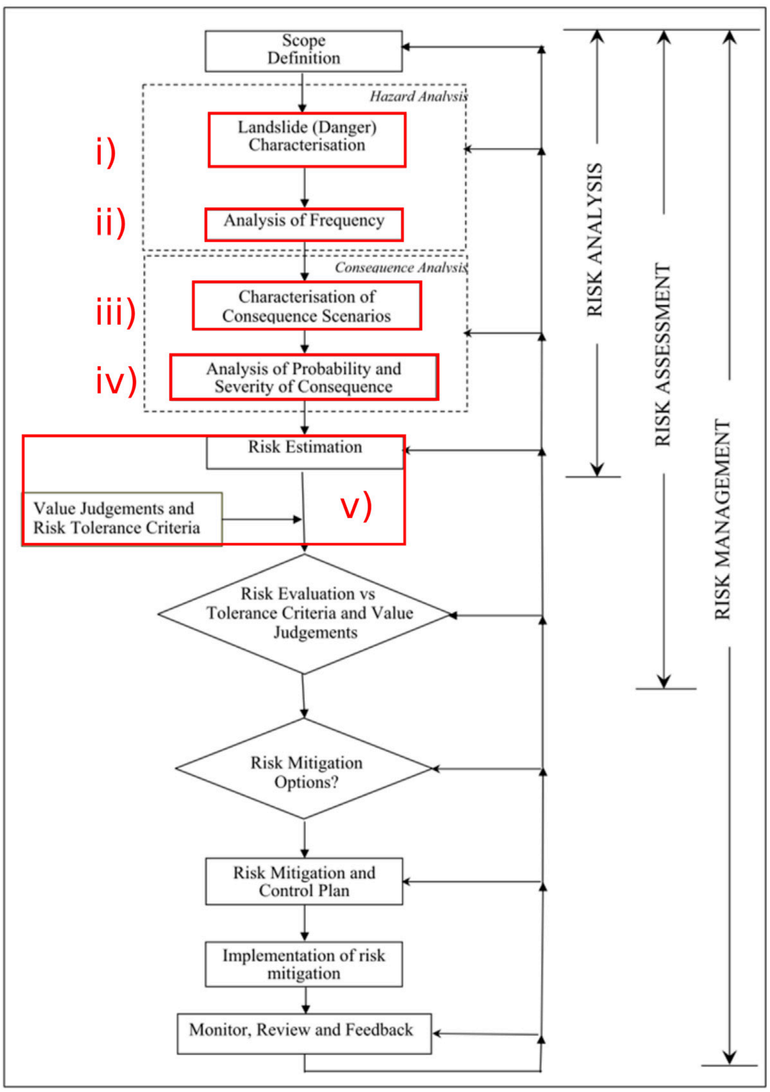

FIGURE 1 | Flow chart of landslide risk management, modified from Hungr et al. (2005) and Fell et al. (2008), red boxes highlight the "weak points".

et al., 2016), appears particularly suitable to develop a more exhaustive establishment of the relationships between landslides and affected slopes, as compared with traditional, symbol-based landslide inventories and maps (Campobasso et al., 2018a; Campobasso et al., 2018b).

Also, the quantitative assessment of landslide risk focuses on the liabilities and responsibilities of the involved parties, providing a reliable framework to put the uncertainties of engineering-geomorphological expert judgments into a more robust decisional system. It foresees an open and transparent cognitive process of the critical factors of landsliding and a productive discussion with public administrators, allowing systematic consideration of risk mitigation options and cost-benefit ratios, consistent with the *As Low As Reasonably Practical* (ALARP) principles (Melchers, 2001).

The above-cited literature declares numerous potential sources of error in the landslide hazard and risk zoning process. A few of these include the following weak points from a geomorphological perspective:

1) Limits in the landslide inventory map on which the susceptibility map and the hazard map are based,
2) Limits in the stationarity of the time series,
3) Limits in the available level of detail of the topographic, geological, and geomorphological map, of rainfall data, and other input data,
4) Uncertainties of the model, thus meaning the limits of the methods used to relate the inventory, topography, geology, geomorphology, and triggering causes in the analysis of susceptibility, hazard, and risk from landslide,
5) The inexperience of the people called to conduct zoning.

Figure 1 integrates the framework for landslide risk management taken from Fell et al. (2005), highlighting the weak points above described.

In addition, the absence of a shared language between the different scientific-technical operators (geologists, engineers, architects, environmentalists, economists, jurists) and understanding problems with policymakers, stakeholders, and property owners make the risk assessment and mitigation in highly urbanized and infrastructured environments often very problematic.

A noteworthy contribution to the interaction among different scientific, technical, and managing partners in European countries is provided by the INSPIRE (*Infrastructure for Spatial Information in Europe*) Directive. It concerns dictionaries and related hierarchical and multiscalar data coding (Craglia and Annoni, 2007; Masser, 2007), on which the Italian Catalog of Territorial Data Specifications for Geo-Topographic Databases are based.

The Data Specifications for Geology and Natural risk zones are reported on the INSPIRE website (TWG-GE, 2013; TWG-NZ, 2013). Concerning the Geology Theme, the Data Specifications indicate 3 Application schemas: 1) Geology; 2) Hydrogeology; and 3) Geophysics. For the basic Geomorphologic Features, Landform is defined as: "*An abstract spatial object type describing the shape and nature of the Earth's land surface*". The framework for slope and gravitational features is reported in **Table 1**.

In order to overcome these limits, uncertainties, and unshared languages, a wide integrated multidisciplinary project for assessing and mitigating the landslide risk of hillslopes in a broad area was performed in the Campania region (southern Italy). The author's contribution in such a project was based on large-scale object-oriented inventory mapping of landslides and advanced working procedures, including standardization (Bernstein, 2015) and exchange-interoperative aspects. The overall project was focused on the evaluation of the landslide risk affecting infrastructures along the coastal stretch between Salerno and Cava dei Tirreni. In the following sections, after an overview of the project, the application of an original object-oriented data model for landslides (LOOM, Valiante et al., 2021a) will be discussed, along with its comparison with geomorphometric techniques for landslide-related features recognition.

2 THE OBJECT-BASED LANDSLIDE INVENTORY MAPPING SYSTEM

Landslides may interact with inhabited areas, infrastructures (such as roads, tunnels, bridges, viaducts, railways), land properties, or sites of cultural interest, often causing heavy damages and loss of lives (Petley, 2012). Assessing the risks associated with landslide impact on human communities requires accurate landslide inventories and large-scale maps highlighting the landslide details, the litho-technical characteristics of the affected slopes, the relationships with other surface and near-surface conditions and gravity-driven processes that may favor landslide triggering or reactivation, and the anthropogenic features that are likely to be involved.

Landslide inventories and landslide susceptibility maps aimed to assess landslide hazard and risk, at different scales, have become increasingly widespread since the past mid-century (Guzzetti et al., 1999; Corominas et al., 2014; Reichenbach et al., 2018). However, only large-scale detailed approaches can be considered reliable to assess the landslide risk in densely urbanized areas (Coltorti et al., 1986; Parise, 2003; Morelli et al., 2018).

Moreover, considering that the destructive impact of landsides is often due to complex overlaps and interaction of different type of slope movements rather than a single one (Cascini et al., 2008; Valiante et al., 2016). Considering that the standard inventory archiving and mapping formats are unable to handle this complexity, the currently used methods are generally unable for assessing landslide risk at site level.

A new object-oriented approach, LOOM (Landslide Object-Oriented Model), has been recently proposed by Valiante et al. (2021a). This model examines the spatiotemporal relationships of landslides within a functional landslide association, including their horizontal and vertical topological relationships, defined as representative of their "under-over" and "old-young" spatial and temporal arrangements. Its basic assumption is that the single objects (single landslides) are represented entirely, including

TABLE 1 | INSPIRE data specifications for slope and gravitational features.

Annex	2
Data theme	Geology
Application schema	Geology
Feature type	Geomorphologic Feature
Spatial object type	Natural Geomorphologic Feature

Attribute	Definition	Multiplicity	Stereotypes	Valuetype <value>	inherited	inherited from
natural Geomorphologic Feature Type	The type of the natural geomorphologic feature	1	-	NaturalGeomorphologicFeatureTypeValue <slope and gravitational features>	no	-
activity	The level of activity of the natural geomorphologic feature	0.1	voidable	GeomorphologicActivityValue <active, dormant, inactive, reactivated, stabilised>	no	-
inspire Id	External object identifier of the spatial object	1	-	Identifier <local Id + namespace + version Id>	yes	GeologicFeature
name	The name of the geologic feature	1	voidable	CharacterString <name of notable landslides>	yes	GeologicFeature

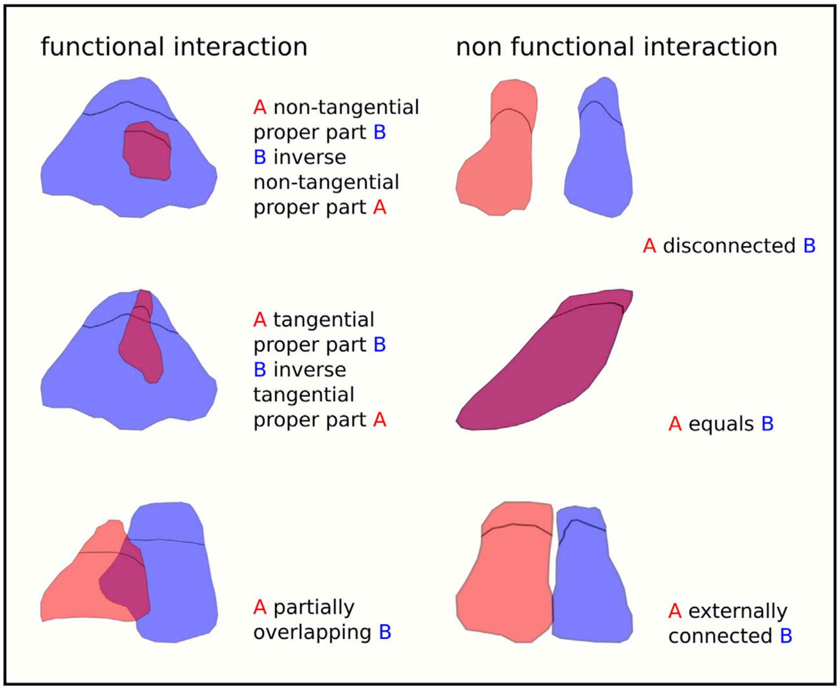

FIGURE 2 | Topological relations between landslide sets reinterpreted from their non functional/functional interactions (after Valiante et al., 2020).

overlapping parts with other objects, in such a way as to preserve their spatial relations and, indirectly, also the temporal ones. The above-below sorting is then carried out in the display phase on a temporal basis, both absolute and relative. In particular, LOOM defines a specific ontology to describe landslide associations and their space-time relationships by implementing them in a database structure capable of storing both spatial and temporal information in a single dataset, avoiding the fragmentation of the data and the related logical-topological inconsistencies (**Figure 2**).

This structure allows to quickly derive information about the number of interacting landslides, their relative occurrence (hence the evolution of a slope), the spatial relationships among them, and those with the surrounding non-gravitational landforms or anthropogenic features.

LOOM is based on the hierarchical, object-oriented classification model (**Figure 3A**) introduced in Valiante et al. (2020). It partially follows Campobasso et al., 2018a, Campobasso et al., 2018b, the new Italian inter-institutional project for a full-coverage and GIS-supported geomorphological mapping

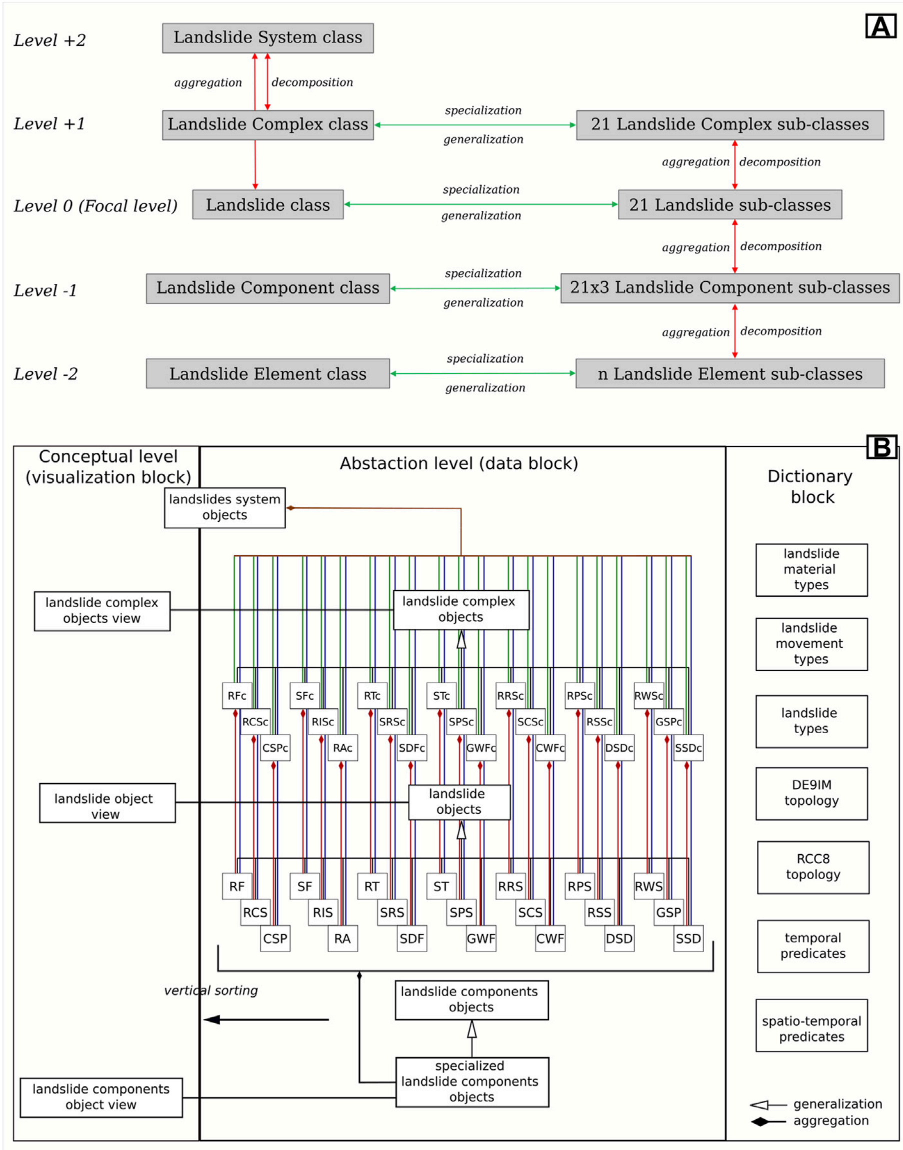

FIGURE 3 | (A) Hierarchical relations among Landslide Classes, subclasses and superclasses; **(B)** Database main structure, each box is a table or a materialized view; table names abbreviations: RF, rock fall; SF, soil fall; RT, rock topple; ST, soil topple; RRS, rock rotational slide; RPS, rock planar slide; RWS, rock wedge slide; RCS, rock compound slide; RIS, rock irregular slide; SRS, soil rotational slide; SPS, soil planar slide; SCS, soil compound slide; RSS, rock slope spread; GSP, granular soil spread; CSP, cohesive soil spread; RA, rock avalanche; SDF, soil dry flow; GWF, granular soil wet flow; CWF, cohesive soil wet flow; DSD, deep-seated slope deformations; SSD, shallow slope deformations, "c" stands for "complex" modified from Valiante (2020).

guidelines, and it stands as a reference for their future developments addressed to land planning activities at national, regional, and local levels.

The LOOM hierarchy defines a multi-level parent-child relationship system where each level can be composed with others into super-level or be broken down into sub-levels until no further decomposition is possible (Simon, 1962; Tsichritzis and Lochovsky, 1976; Singh et al., 1997; Odum and Barrett, 2005; Wu, 2013). Hierarchical levels depend on the purpose to which they are applied: the center of the hierarchy (*focal level*) can be any single landslide object of interest, parents define its generalization or aggregation levels, and children define its levels of specialization or decomposition (Wu, 1999; Wu, 2013). Two levels of aggregation describe sets of landslides: 1) landslide complexes, resulting from the aggregation of spatially connected landslides of the same type (level +1), and 2) landslide systems, defined as spatially connected sets of landslides of different types (level +2). Two other levels describe the landslide structure: 3) landslide components (level -1), and 4) landslide component elements, not further decomposable (level -2). The hierarchy's focal level (level 0) is defined by the landslide class, comprising 21 subclasses based on the Hungr et al. (2014)

TABLE 2 | Proposed slope and gravitationa sub-types and LOOM equivalent classes.

Proposed natural geomorphological feature sub-types	LOOM classes
slope and gravitational geo-morphological unit	-
slope and gravitational system	landslide system class
slope and gravitational complex	landslide complex class and its sub-classes
slope and gravitational unit	landslide class and its sub-classes
slope and gravitational unit component	landslide component class and its subclasses
slope and gravitational unit component element	landslide element class and its sub-classes

landslide classification. In **Table 2** LOOM levels and classes are related to proposed slope and gravitationl features sub-types within the Natural Geomorphologic Feature spatial object type.

The database management system used for LOOM is PostgreSQL © 11.0 with PostGIS © 2.5 extension (versions at compiling time). Database maintenance and manipulation are achieved using PgAdimn4 and the "pgcli" command-line tool, while QGIS 3.4 LTR © is used for data query and visualization. Such infrastructure is completely open source, and it can be easily implemented even on not so sophisticated systems favoring a wide access to the procedure (Valiante, 2020).

Based on the conceptual model described above, the database has been structured into three main blocks: a dictionary, data, and visualization. In the dictionary block, tables containing reference terminology are included. The main purpose of this data is to prevent errors during the process of data entry, therefore, to maintain data integrity. These tables are accessed through foreign keys by the tables contained in the data block and by some of the dictionary tables themselves. The terminology contained in this block is about landslides (Hungr et al., 2014) and spatio-temporal topology semantics (Allen, 1983; Egenhofer and Herring, 1990; Randell et al., 1992). The defined tables are listed in **Figure 3B**. The data block is structured to contain the instances of the object-oriented model. Here, a table is defined for every class declared in the model, meaning that the final result will be having 21 tables for landslide objects, 21 tables for landslide complex objects, and one table for landslide systems. Tables for landslide components and landslide component element are implemented based on the needs. Landslide complex tables are materialized views derived from the aggregation of the landslide subclasses tables where the functional interaction is satisfied. These objects do not have an exact temporal characterization as they can contain different landslides that occurred at several times, but their vertical sorting is achieved by computing the "mean event" from the aggregated landslides events so that the most active complexes are ensured to be on top. Similarly to the previous tables, the landslide systems table is a materialized view built upon the aggregation of the previous data. As for landslide complexes, systems do not have an exact temporal characterization. Moreover, considering how they are built, the vertical arrangement of landslide systems is invariant as for their definition they cannot overlap: absurdly, if two or more landslide systems overlap, the functional relation is verified; thus, they will be aggregated again into a single landslide system. In the visualization block, objects from the data block are re-arranged for the correct visualization. The vertical sorting is applied using the temporal characterization of landslides. This process only applies to components, landslides, and complexes as systems do not overlap (Valiante, 2020; Valiante et al., 2021a).

A relevant aspect of LOOM concerns its ability to describe the topological relationships between the considered landslide objects whose cartographic representation includes overlapping parts with other objects in such a way as to preserve their spatial relations and, indirectly, also the temporal ones.

Traditional geomorphological mapping represents landforms as polygons juxtaposed with each other with shared edges according to a pattern that could be defined as "tile" or "mosaic". This procedure defines an information level that "cloaks" the area of interest without overlapping the entities belonging to the same table. Although this model may be helpful in numerous applications, such as cadastral data and administrative boundaries, it is entirely insufficient for a correct cartographic representation of geomorphological data. The mosaic of landforms creates a conceptual inconsistency between the mapped data and the reality, where landforms are often spatially superposed, functionally interacting, and structurally interconnected where topological relations are the only reliable conceptual approach.

In this context, it is indispensable a data structure capable of maintaining those topological relationships that best approximate the actual in-field situation. In particular, it is crucial to maintain the spatial superposition ratios according to a 2.5D or even 3D model.

This approach could be also extended to the relations existing between natural geomorphological features and anthorpogenic features (infrastructures, pipelines, buildings, industries, etc.). An emblematic example regards the spatial relationships between a watercourse and a bridge crossing it: in a 2D mosaic representation, there will be a spatial intersection between the watercourse and the infrastructure, with all the relative consequences in the contexts of danger and hydrogeological risk; if, on the other hand, the two objects are analyzed in a 3D scenario or in one that still takes into account the superimposition relationships, it could even result that the two objects do not come into contact at all, that is, they are disjoint from a topological point of view (**Figure 4**).

3 THE CIS_2020 REGIONAL PILOT PROJECT

On July 29th, 2019, the Campania Regional Administration, in agreement with the seven regional universities (C.U.R. - Regional University Committee), launched the multidisciplinary project entitled "*Methodologies for the Punctual Assessment of Hydrogeological Risk in Densed Anthropized Areas and Tools for Regional Development Strategies*".

The project has been granted in the perspective of promoting advanced, interdisciplinary, and shared models for assessing, managing, and monitoring landslide risk in critical areas. Such critical areas are characterized by strategic infrastructures concentrated in an urban environment of high socio-economic

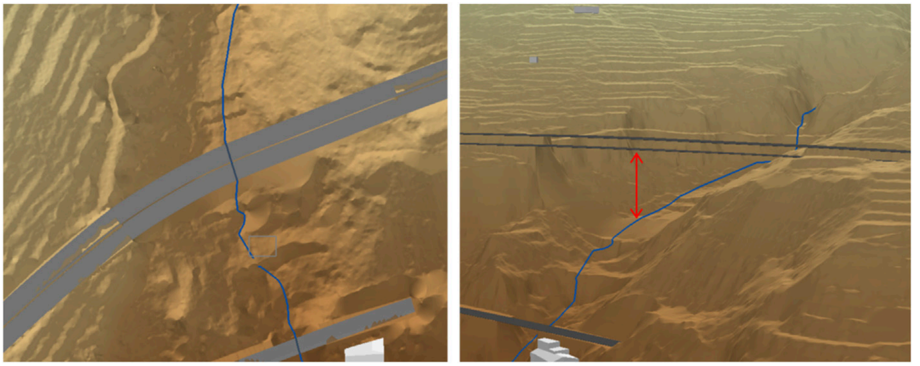

FIGURE 4 | - On the left, apparent 2D intersection between the river and the bridge; on the right, the same scene in a 3D view.

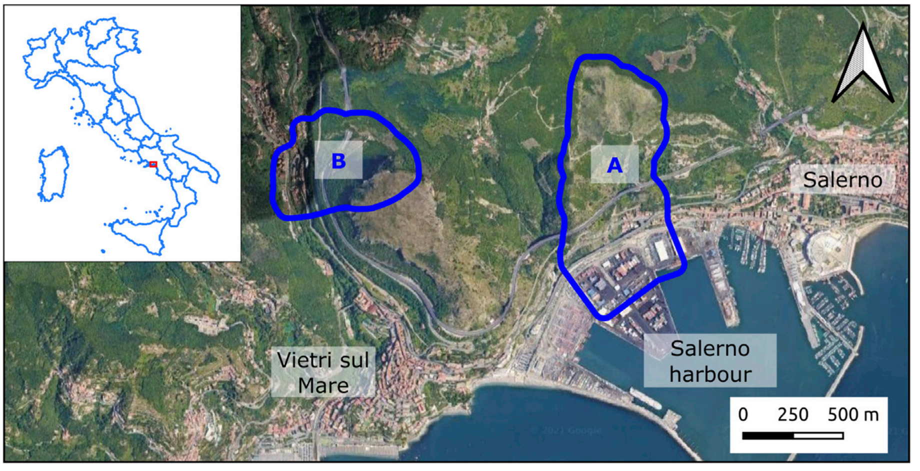

FIGURE 5 | Location of the investigated area, the in-depth study areas are outlined in blue: **(A)** Olivieri catchment; **(B)** Mt. San Liberatore north-western slope (image from Google repositories).

value. The project aimed at improving the technical-administrative capacities and multi-level governance of public offices in the perspective of new standardization supports.

The selected study area is the Salerno - Cava dei Tirreni *Strategic Infrastructural Corridor*, a 5 km^2 wide strip of the Southern Apennine Tyrrhenian borderland of highest national and regional socio-economic value, between Salerno town to the East, and Vietri Sul Mare, a very popular touristic center ("*the Eastern Door*" of the Amalfi Coast) to the West. Key transport infrastructures cross this area among which: a section of the A3 Naples-Salerno Highway; the Salerno-Cava dei Tirreni railway; the SS18 "Tirrena Inferiore" state road; the regional roads to the Amalfi Coast; and the connecting roads to the commercial and touristic Salerno Harbor System (**Figure 5**).

The geological structure of the project area is characterized by a Mesozoic carbonatic sedimentary sequence belonging to the Apennine Platform Complex thrusting over the Lagonegrese-Molise Basin terrains and locally affected by NW-SE and SW-NE trending low-angle/high angle normal faults (Vitale and Ciarcia, 2013). The near-surface units include alluvial deposits consisting of gravels in a sandy matrix, cemented slope debris, and Pleistocene to recent volcano-clastic and pyroclastic deposits, erupted by the Mt. Somma-Vesuvius volcanic complex (Cascini et al., 2008).

The geomorphological features of the study area are those typical of the Amalfi Coastland, with high relief, coastal carbonate hillslopes incised by deep ravines and gullies, and large headwaters with zero-order basin complexes (Cascini et al., 2008) filled by residual pyroclastic covers. In the nearshore, coastal cliff complexes are alternating with narrow pocket beach complexes. To the Western and Eastern borders are located the coastal plain of the Bonea Torrent and Irno River, respectively. To the NW border of the study area, the cuesta-like morpho-structure of Mt. San Liberatore is the more prominent landscape in the area. It is surrounded by litho-structural cliffs (**Figure 5**).

Landslides are widespread and frequent: mostly rockfalls and debris avalanches from limestone escarpments and earth-mud flows from pyroclastic hillslope covers in the headwaters, have repeatedly affected the area in the past, even with catastrophic effects (Cascini et al., 2008; Fiorillo et al., 2019) (**Figure 6**). A critical strategic aspect is that any landslide-related interruption

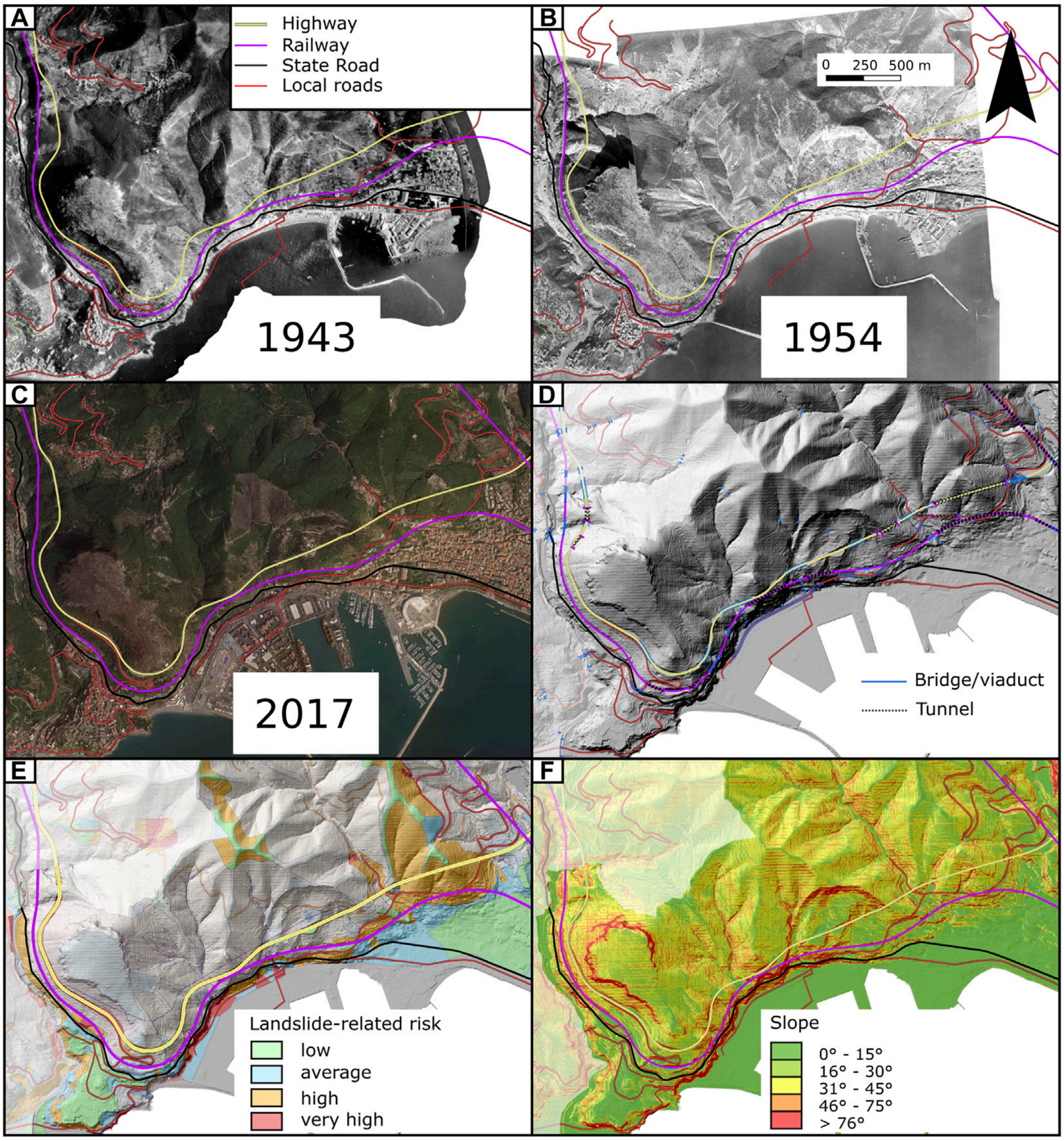

FIGURE 6 | The Strategic Infrastructural Corridor Salerno-Vietri sul Mare study area (CIS2020): **(A)** superposition of the present-day Transport Infrastructure System on the aerial photo taken in 1943 by Royal Air Force—evident surficial scars related to 1909–1910 disaster events; **(B)** superposition of the same CIS2020 on the aerial photo taken by Italian Military Geographic Institute—evident channelled surficial scars and invasion areas by pyroclastic wet material related to the 1954 October 24 disaster event which strongly affected the settlements of Salerno-Amalfi coastland; **(C)** superposition of the present-day CIS2020 on the ortho-photo by Campania Region Archives, taken after the major wildfire event occurred during the summer 2017 in the area from decadal times—evident surficial erosion, scars and incision; **(D)** CIS2020 infrastructures highlighting tunnels, viaducts and bridges over LiDAR data from the National GeoData Repository; **(E)** superposition of the CIS2020 on currently in force Landslide Hazard and Risk of the District basin Authority "Southern Apennines"; **(F)** the CIS2020 on the slope map highlighting scarps, cliffs, and channelized landforms.

in the Infrastructure System could induce relevant economic damage at the national and regional levels.

4 THE LANDSLIDE OBJECT-ORIENTED MODEL APPLICATION OF THE CIS_2020 PROJECT

The specific project targets were improving the technical-scientific methods for quantitative assessment of landslide risk and proposing an advanced territory management system in the perspective of new scientific and interoperation supports. At this end, an updating of the available geo-environmental and infrastructure database of the investigated area was performed to overcome the weak points mentioned before.

Within the CIS_2020 Project, DICIV_UNISA and C.U.G.RI., (University of Salerno) carried out the inventory mapping of landslides over the entire project area, systematically applying the LOOM at the 1:5.000 scale with more detailed scales (1:2000) in sectors of particular interest.

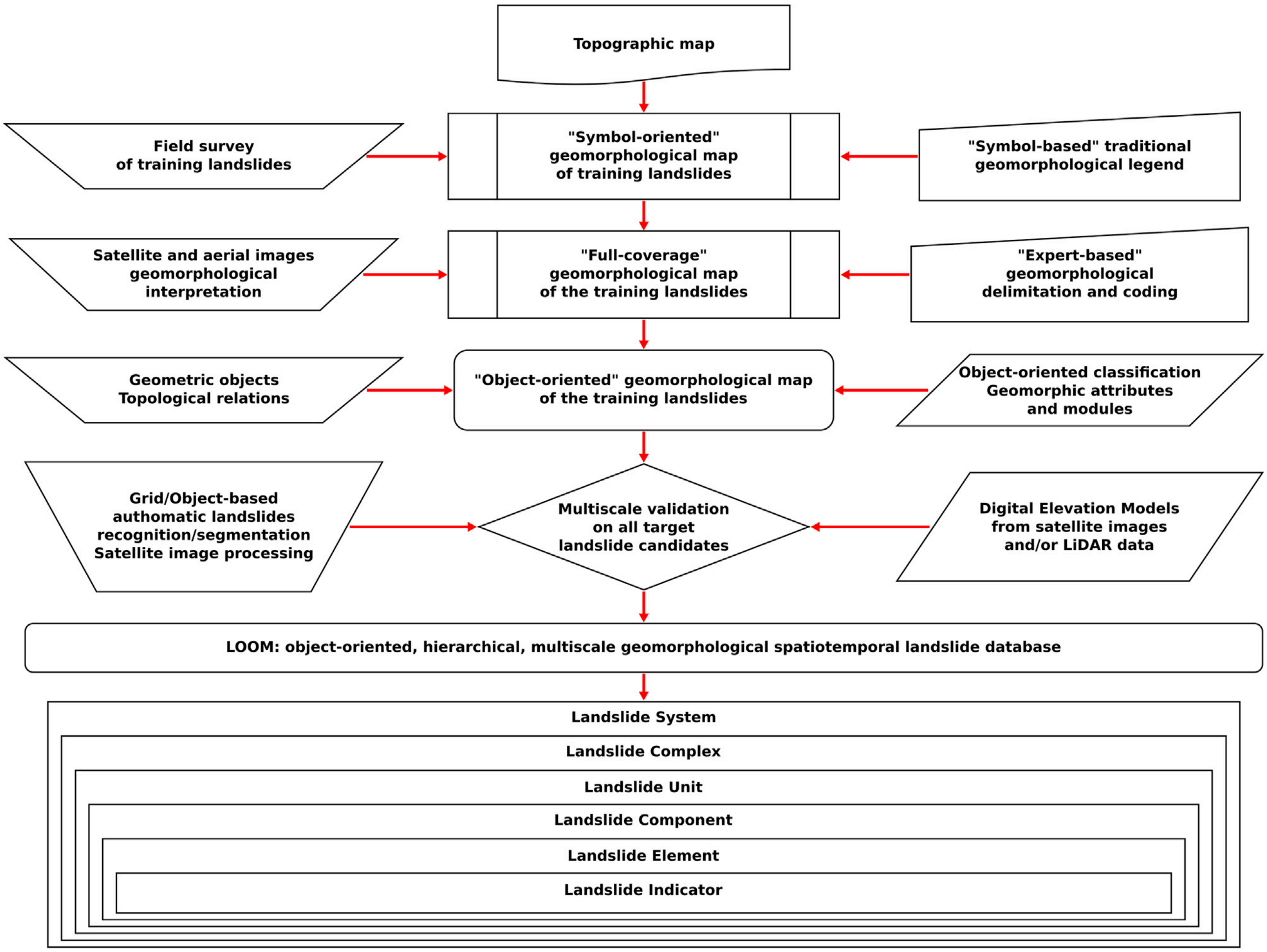

FIGURE 7 | LOOM mapping procedure (modified after Dramis et al. (2011)).

This activity provided the basis for the other interventions (engineering, environmental, economic, and legal) aimed at preparing guidelines for the assessment and mitigation of landslide risk and the required resilience measures to be shared with regional, provincial, and municipal offices.

The morphological features of the natural and built-up environment have been surveyed over time by comparing high-resolution DEMs (Digital Elevation Models) and remote-sensing images, including a very high-resolution satellite (Pléiades) stereo-pair covering the entire investigated area. For the sectors of major detail, ultra-high-resolution drone images and scans from Terrestrial Laser Scanner, capable of detecting the ground beneath the vegetation, were used (courtesy of LabM, DICIV_UNISA).

The spatial inventory has been constructed following Dramis et al. (2011), with further integrations contained in Valiante et al. (2021a) transforming the spatial inventory in a spatiotemporal "eventory" (*sensu* Valiante et al., 2021b). For the initial spatiotemporal mapping of landslides, detailed field surveys were performed, integrating the analysis of remote sensing images, given the need for lithostructural, stratigraphic, sedimentological, and hydrogeological data to avoid geomorphological convergence. After the initial expert-based mapping, data are arranged in the object-oriented data structure (LOOM). Lastly, a multiscale validation has been carried out, exploiting both grid-based techniques and other object-oriented techniques such as OBIA (Object-Based Image Analysis) (Blaschke et al., 2014; Hölbling et al., 2015) (**Figure 7**).

Examples of the LOOM inventory mapping of landslides in two in-depth study areas, the Vallone Olivieri catchment and the Mt. San Liberatore north-western slope (box A nd box B in **Figure 5** respectively), both interesting for the recurrent occurrence of landslides capable of interrupting road and railway lines, are presented below.

In the previous dataset available from the currently enforced Landslide Inventory Map (Campania Sud Regional Basin Authority, 2012; Fiorillo et al., 2019), the October 26, 1954 landslides (Fiorillo et al., 2019) were represented by drawing their outlines or grouping them into comprehensive polygons, classified as extremely rapid mudflows. Data contained in the PAI dataset was based only on the highest magnitude event in the area, that is, the

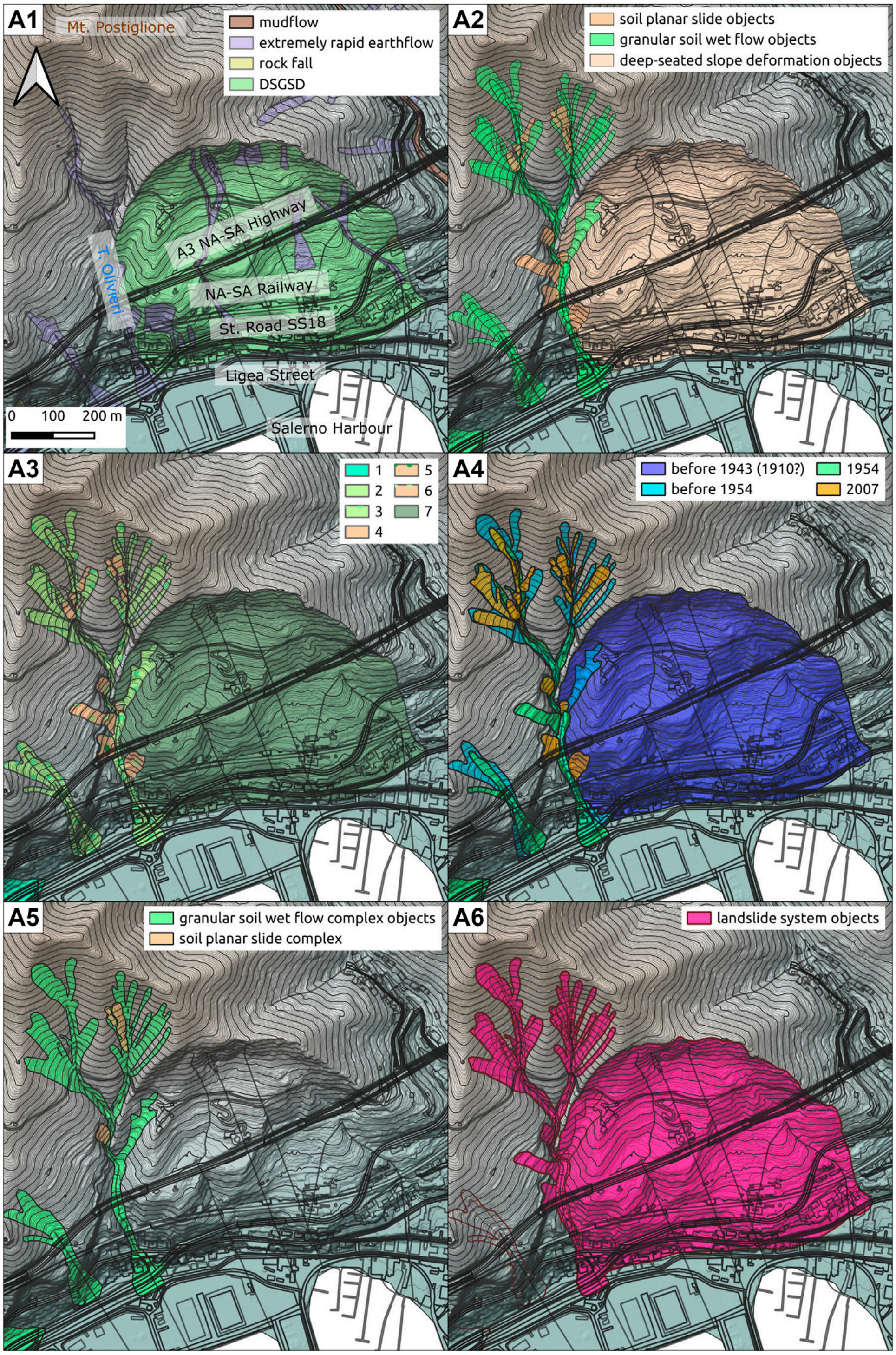

FIGURE 8 | Vallone Olivieri Catchment case study: **(A1)** pre-existing dataset; **(A2)** LOOM focal classes; **(A3)** LOOM landslide types, 1. Debris avalanche, 2. Debris flood, 3. Debris flowslide, 4. Debris flowslide—debris avalanche, 5. Debris flowslide—debris flow, 6. Debris slide, 7. Debris slide—debris dry flow, 8. Debris slide—debris flowslide; **(A4)** LOOM temporal classification; **(A5)** LOOM +1 level; **(A6)** LOOM +2 level.

flow events of 1954. Other minor events, such as small magnitude rock falls, were not taken into account mostly because 1954 flows obliterated them. Successive rock falls, and other small events were also not mapped because the scale of analysis was not supported by field surveys but was performed at the basin scale for planning purposes. In our

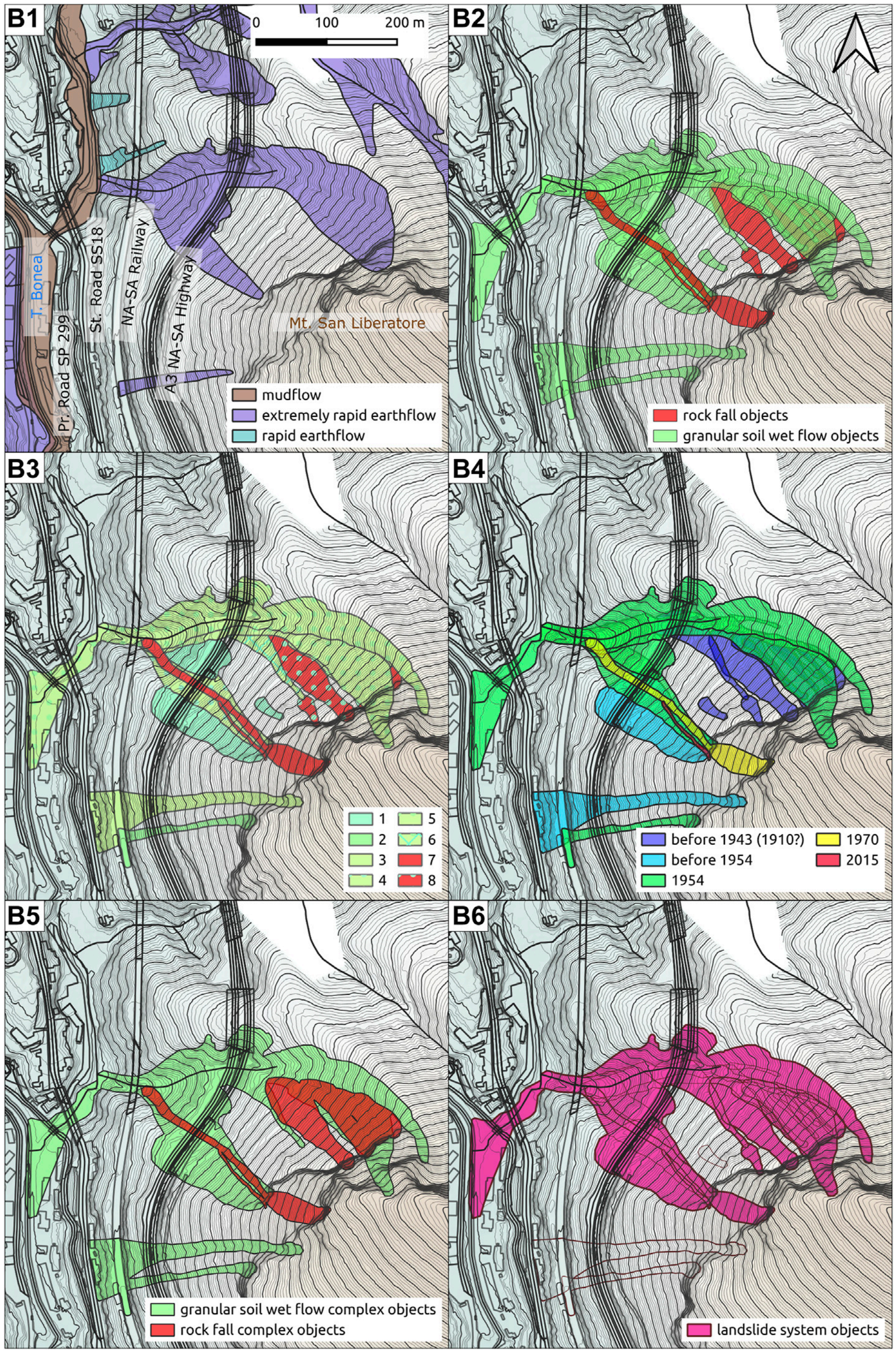

FIGURE 9 | Mt. San Liberatore case study: **(B1)** pre-existing dataset; **(B2)** LOOM focal classes; **(B3)** LOOM landslide types, 1. Debris avalanche, 2. Debris flow, 3. Debris flowslide, 4. Debris flowslide—debris avalanche, 5. Debris flowslide—debris flow, 6. Debris flowslide – debris flow—debris flood, 7. Rock fall, 8. Rock fall—debris avalanche; **(B4)** LOOM temporal classification; **(B5)** LOOM +1 level; **(B6)** LOOM +2 level.

work, instead, we conducted detailed field surveys also based on high-resolution base maps, such as sub-meter lidar data.

The first in-depth study area comprises the North-South-oriented sector of the Olivieri catchment, immediately north of the Salerno harbour. This area is widely affected by flow-like movements, such as debris flowslides and debris flows (sensu Hungr et al., 2014), which fall within the granular soil wet flow class in the LOOM data structure. Besides flows, the area has also recorded a few debris slides (sensu Hungr et al., 2014) stored as *soil planar slide objects*, previously classified as *extremely rapid earth flows* and *debris avalanches* (Fiorillo et al., 2019).

The LOOM data structure allowed more information from the surveyed data than was possible from the previously adopted investigation methods (**Figure 8**). From a multitemporal perspective, it is now possible to classify the entire landslide dataset based on every object's time or period of occurrence. From archive records and local testimonies, flows older than those that occurred during the October 25–26, 1954 event, which are predominant in the area, could be recognized and distinguished. After 1954, a few smaller flows and shallow debris slides, mainly related to wildfires that occurred in 2007 (Calcaterra et al., 2007) and during the 2017 summer (Esposito et al., 2017), have been inventoried. Moreover, the LOOM hierarchical aggregation procedure allowed handling landslides' spatial and temporal overlap.

All the *granular soil wet flow objects* were aggregated into one *granular soil wet flow complex object* because of their functional interaction relationships (filling-discharging-refilling in Guida, 2003). For the same reason, a cluster of *soil planar slide objects* affecting the north-eastern area could be aggregated into a *soil planar slide complex object* (retrogressive and successive sliding). Other objects of the same class could not be aggregated because they were disjoint. With the second aggregation steps, the set of all the inventoried *landslide objects* was aggregated into a single *landslide system object*, which exemplifies the evolution of the basin characterized by recurrent flow-like movements along the main valley trunk, which are feed, in turn, by shallow debris slides from the valley flanks (**Figure 8**).

The second in-depth investigated area, Mt. San Liberatore's north-western slope, is recurrently affected by rockfalls and debris avalanches from the upper part of the slope, characterized by calcareous rocky cliffs, and debris flows involving the pyroclastic covers (**Figure 9**). The previous inventory reported for this area a single landslide feature classified as "extremely rapid mudflow" from pyroclastic soils (Fiorillo et al., 2019). With the LOOM approach, these phenomena have been classified respectively as *rockfall objects* and *granular soil wet flow objects*.

Applying the LOOM data structure, the chronology of the landslide events has been registered not only as visual overlap of entities but also as functional interaction of events, thus their recurrence. As for the Vallone Olivieri area, the most extensive flow features occurred during the October 25–26, 1954 event, preceded by a few older ones. Besides flows, the inventoried rock fall objects from local testimonies and archive data date back to 1970 (the larger one) and 2015. The first step of the aggregation procedure allowed the definition of a *granular soil wet flow complex object* and a *rockfall complex object*, highlighting the repetitiveness of the events. The second aggregation step defined a single *landslide system object* resulting from the spatiotemporal succession of debris flows, debris avalanches, and rockfalls (**Figure 9**).

5 QUANTITATIVE ASSESSMENT OF GRAVITY-DRIVEN REFERENCE HILLSLOPES AND PROCESS DOMAIN

In order to quantify the expert-judgment procedures morphometric indexes have been exploited. Such indexes are the Topographic Position Index (TPI) proposed by Weiss (2001), for the semi-quantitative delineation of main landforms, and the Slope-Area plots, for the estimation of the slope processes typology, including the gravity-driven ones (Vergari et al., 2019). The analyses were based on Digital Elevation Models with different resolutions for the wide area (2 m resolution) and the more detailed excerpts for the in-depth study areas (0.2 m resolution).

The Topographic Position Index (TPI) proposed by Weiss (2001), defined as the difference in elevation between a point and the average of its neighborhood, was applied to design the topographic basis on which to superimpose the surveyed geomorphological features (**Figure 10**). The TPI values were classified using three progressive hierarchical levels: Basic Topographic Units (UTB - Campobasso et al., 2018a; Campobasso et al., 2018b); Slope Positions (Weiss, 2001), and Relief Shapes (the landforms defined within this project). The starting point for this classification was the definition of the Slope Positions based on the classification of the TPI values (**Table 3**); the UTBs were derived by aggregation of the Slope Positions, and the Relief Shapes were obtained from a further decomposition of the Slope Position with the addition of their slope values, according to the scheme shown in **Table 3**.

Slope - Area Plots (Booth et al., 2013; Tseng et al., 2015) have been exploited to estimate the denudational process types acting on the slopes, including landslide phenomena. The purpose of this analysis is to detect the hypothetical landslide-related channels as a validation tool for the detected flow-like landslides.

The graphical plot of the topographic steepness versus the drainage area can be subdivided into four main regions or segments, each one representing a dominant geomorphic process: I) hillslopes; II) hillslope-to-valley transition; III) debris flow dominated channels or landslides driven channels; IV) alluvial channels. Slope and contributing area values have been plotted for each case study, and domain thresholds have been defined, analyzing the slope derivative values (Vergari et al., 2019).

Generally, the threshold for the I – II boundary has been set at the first zero value of the slope first-order derivative, corresponding to the maximum value of the Slope – Area plot; the threshold between II and III domains has been set at the next zero of the first-order derivative function which reflects an interruption in the steady decreasing trend of the II domain; the last threshold is marked by the last zero of the first-order derivative values corresponding to the transition from fluctuating values to a steady decreasing trend in the slope plot. For this study, instead, classes I and III have been further subdivided to better exploit the high resolution of the grid dataset, also analyzing the second-order derivative of the plot (**Figure 11A**):

- Ia) Areal diffusive processes on ridges and spurs: this is the first segment of the slope-area plot characterized by an initial rising of the slope along with the drainage area up to the peak point of the plot;
- Ib) Areal diffusive processes on shoulders: after the peak point of the plot, the previous trend is reverted, and the slope starts to decrease as the drainage area increases;

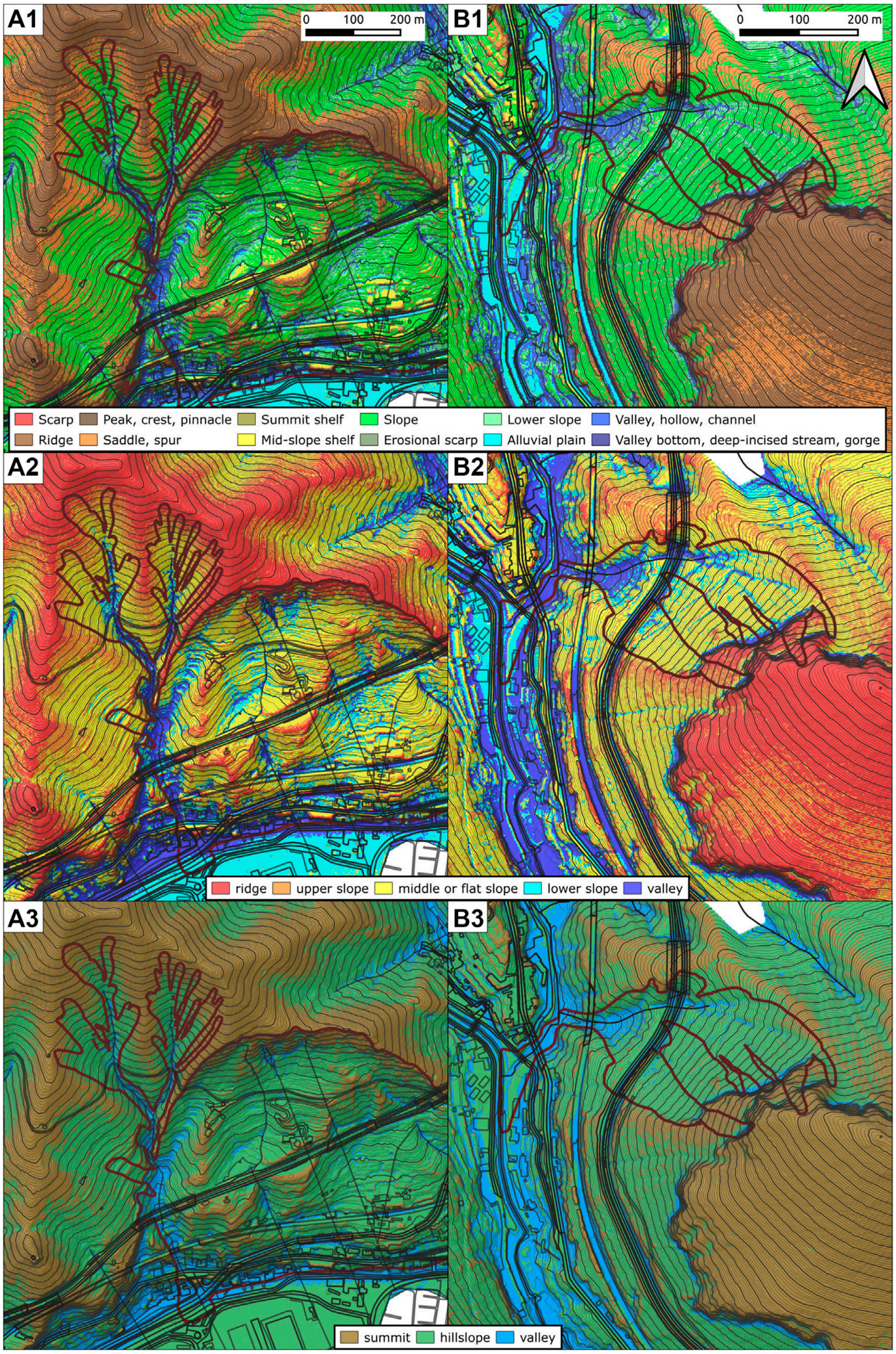

FIGURE 10 | TPI elaborations for the selected case studies: **(A1)** landforms, **(A2)** slope positions, **(A3)** Basic Topographic Units for the Olivieri case study; **(B1)** landforms, **(B2)** slope positions, **(B3**) Basi Topographic Units for the Mt. San Liberatore case study. Landslide system objects are outlined in dark red.

II) Concentrated erosional processes: the second threshold is identified at the first curvature center of the slope-area plot, corresponding at the first max point or min point of the second-order derivative of the slope-area plot;

IIIa) Transitional erosional processes: the third threshold is identified at the first inflection point of the slope-area plot, corresponding to the first zero value of the second-order derivative of the plot;

TABLE 3 | Multiscale segmentation of TPI values.

UTB	Slope positions	Landforms
Summit	TPI > std = Ridge	TPI > std & p > 60° = Scarp TPI > std & 5° < p ≤ 60° = Ridge TPI > 2std & p ≤ 5° = Peak, crest, pinnacle std < TPI ≤ 2std & p ≤ 5° = Summit shelf
	0,5std < TPI ≤ std = Upper slope	0,5std < TPI ≤ std & p > 60° = Scarp 0,5std < TPI ≤ std & p ≤ 60° = Saddle, spur
Slope	-0,5std < TPI ≤ 0,5std = Middle slope	-0,5std < TPI ≤ 0,5std & p > 60° = Scarp -0,5std < TPI ≤ 0,5std & 5° < p ≤ 60° = Slope -0,5std < TPI ≤ 0,5std & p ≤ 5° = Mid-slope shelf
	-std < TPI ≤ -0,5std = Lower slope	-std < TPI ≤ -0,5std & p > 60° = Erosional scarp -std < TPI ≤ -0,5std & 5° < p ≤ 60° = Lower slope -std < TPI ≤ -0,5std & p ≤ 5° = Alluvial plain
Valley	TPI ≤ -std = Valley	TPI ≤ -std & p > 60° = Erosional scarp -2std < TPI ≤ -std & 5° < p ≤ 60° = Valley, hollow, channel -2std < TPI ≤ -std & p ≤ 5° = Alluvial plain TPI ≤ -2std & p ≤ 60° = Valley bottom, deep-incised stream, gorge

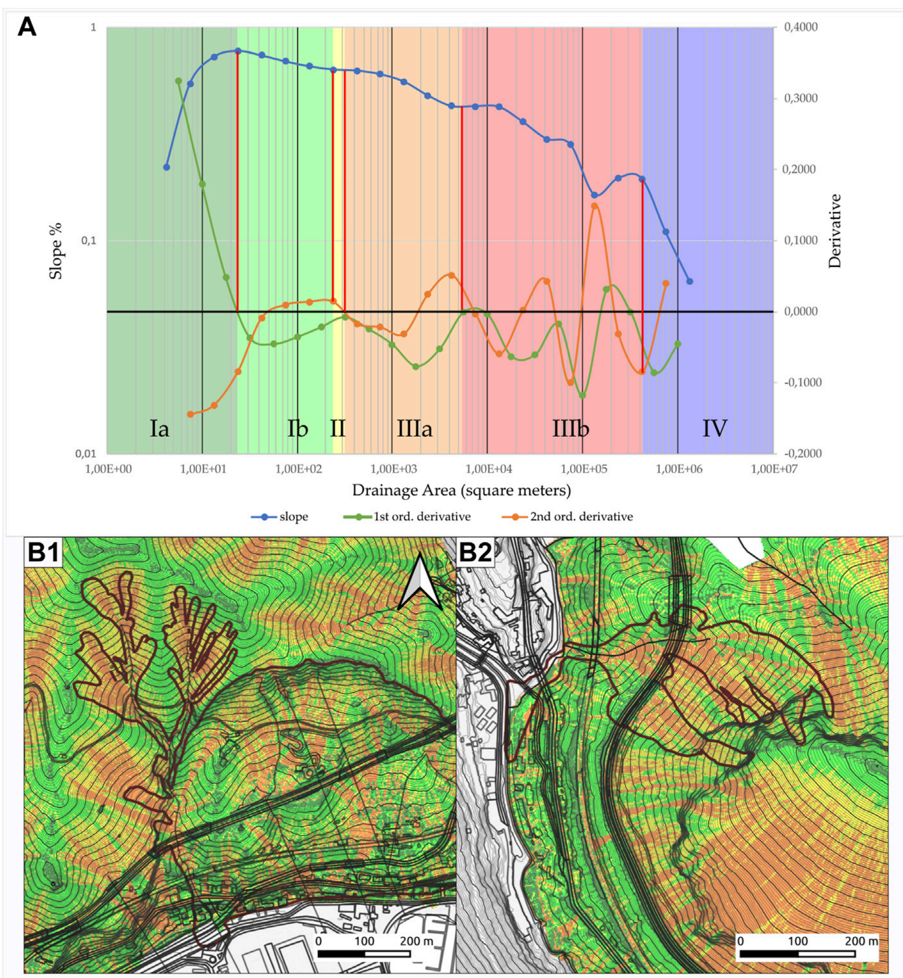

FIGURE 11 | (A) Slope-Area plot for the investigated area; **(B)** Process Domains maps for the selected case studies: **(B1)** Olivieri and **(B2)** Mt. San Liberatore. See insert **(A)** for color legend, landslide system objects are outlined in dark red.

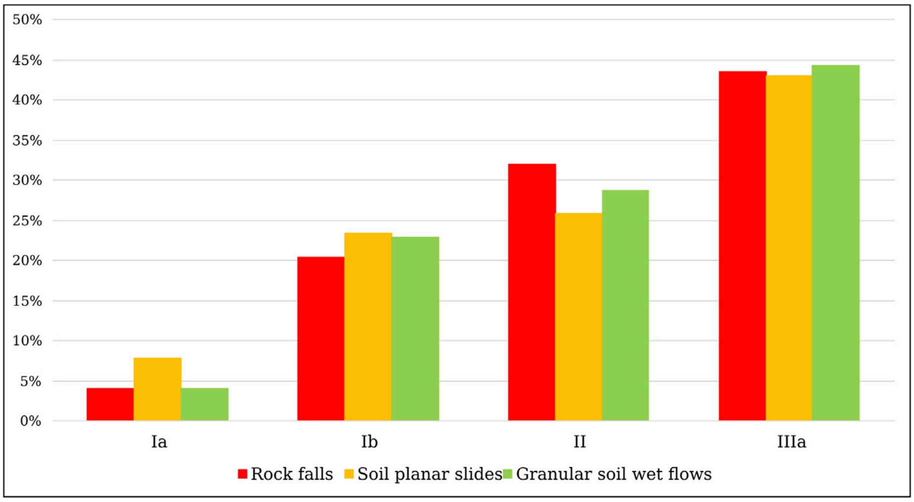

FIGURE 12 | Histogram showing process domain percentage cover for each landslide class.

IIIb) Channeled depositional-erosional processes: the fourth threshold is identified at the first slope inversion in the slope-area plot, corresponding to a zero value of the first-order derivative of the plot;

IV) the last threshold is identified at the last segment of the plot, which is characterized by a steady decrease of the slope; it corresponds to the last inflection point of the plot.

Figure 11B is the spatial expression of the thresholds identified in **Figure 11A**, mapped on a 2 m resolution DTM derived from LiDAR data available in the Italian National GeoData DB. From comparing LOOM data and the resulting surficial processes grid, we demonstrated not only a good visual correlation, but also a preliminary quantitative correlation between debris avalanches, debris flows and the IIIa region of the slope-area plot. For simplicity, the histogram of **Figure 12** shows such correlation.

5 DISCUSSION

With the Union Civil Protection Mechanism (UCPM) Decision No 1313/2013/EU EU, Member States and UCPM participating states are requested to report to the Commission on their disaster risk management activities to support formulating an EU risk management policy that would complete and enhance the national ones. In this framework, the new "Reporting Guidelines on Disaster Risk Management (2019/C 428/07), referring to the Art. *6(1) d* of the above Decision," is aimed to support the use of the Guidelines by relevant national authorities (Poljanšek et al., 2019).

The European Commission, using the Joint Research Centre (JRC), joins national, regional, and global efforts to acquire a better risk governance structure through 1) evidences, 2) science, and 3) knowledge management. Risk governance facilitates the policy cycle to implement integrated disaster risk management. In order to promote an effective and coherent approach to the prevention of and preparedness for disasters by sharing non-sensitive information and promoting the exchange of best practices within the Union Mechanism, Member States shall: 1) further develop risk assessments at national or appropriate sub-national level; 2) further develop the assessment of risk management capability at national or appropriate sub-national level; 3) further develop and refine disaster risk management planning at the national or appropriate sub-national level.

In addition, INFORM partners (Thow et al., 2021) believe that the availability of shared analysis of crises and disasters can lead to better coordination of actors and better outcomes for at-risk and affected people. Specifically, INFORM creates a space and a process for shared analysis to support joint strategy development, planning, and action to prevent, prepare for, respond to and recover from crises. This approach can bring together development, humanitarian and other actors to manage risk and respond better when crises occur. The report sets out by INFORM's vision for a suite of products to support decision-making easy to use and open to everyone. This vision involves bringing scientific rigor to the process of analyzing crises and pooling expertise to develop shared methodologies. By working together, we can reduce the investments required by individual organizations, assure the quality of our analysis and make it available for the common good.

In order to pursue the EU recommendations concerning landslide risk assessment, the geomorphological working group pilot supported the project above illustrated followed two approaches: expeditious (regarding inspections and classification) at the whole territory level and punctual quantitative landslide hazard assessment focused on individual built-up structures. In particular, the project results indicate that, while the risk associated with rockfalls in the entire area is rather low apart from some limited sectors, that related to debris flows mobilizing pyroclastic deposits above the carbonate slopes is much higher and more widespread.

The common application of the European INSPIRE Directive and the Italian National Catalog of Territorial Data with the related Geo-Topographic DB allowed data transferring and transdisciplinary interoperability between universities and public authorities involving academic researchers and regional technicians and officers, responsible of Civil Protection, and technical-administrative managers of the infrastructural network.

In this perspective, such data structures should also be used for the information concerning the analysis and the evaluation of environmental hazards and risks. The LOOM data structure provides an application for landslide data. The hierarchical classification of landslide sets based on objective topological operators results in a better understanding of landslide relations and provides a standard semantic approach in storing and retrieving such information. Moreover, the very concepts of landslide complex and landslide system are proxies for other characterizations such as repetitiveness and evolutionary trend, as stated in Valiante et al. (2021b). The temporal classification, instead, adds frequency information to repetitive events. Both the hierarchical and temporal classifications aim to better define the landslide hazard, contributing to the landslide characterization and the frequency assessment, namely weak points 1) and 2) of the risk management procedure mentioned in the previous sections.

The interoperability of object-oriented data structures, such as LOOM and Geo-Topographic databases, allows the analysis of the interaction between landslides and vulnerable features, such as infrastructures, in a 2,5D or even 3D framework, surpassing a simple 2D intersection, for a better understanding of consequence scenarios, thus providing for the weak point 3) of the risk analysis procedure. Moreover, a more robust definition of the topological relations between hazardous and vulnerable entities, coupled with the concept of repetitiveness contained in landslide complex definition, and the "domino effect" concept proper of the landslide system construct, can also help in the analysis of probability and severity of consequences (weak point iv).

The analysis of the Slope-Area plot provides a correlation between process domains and landslide features, at least regarding flow-like movements, being the majority of the inventoried phenomena, thus the most representative. As shown in the maps of **Figure 11B** and the histogram of **Figure 12**, about 75% of the landslide area falls within the erosional process domains. In detail, the average value of 30% is represented by concentrated erosional processes, and the average value of 45% is represented by transitional erosional processes. Looking at how these domains are distributed within landslide objects, areas characterized by the process domain II could be related to detachment areas, which are contained mostly in the Hillslope UTB but also in the Summit UTB as defined through the TPI analysis; while areas characterized by the process domain IIIa could be related with transit zones or flow channels, which are contained both in the Hillslope and the Valley UTBs.

6 CONCLUSION

In this paper, the authors develop a proposal to better manage the key issues concerning the following questions posed by Reporting Guidelines on Disaster Risk Management (Poljanšek et al., 2019), addressing new insights on weak points on landslide risk assessments, landslide risk management capability, and priority prevention and preparedness measures:

- advancing shared languages for landslide risk assessment process, using the GeoUML international standards and the LOOM semantics;
- landslide mapping using object-oriented EU INSPIRE interoperable data management, starting from a landslide inventory built with the LOOM data structure;
- communicating risk assessment results using trans-disciplinary consultations with relevant authorities and stakeholders, using the Italian National Data Structure of Geo-Topographic DataBases coherent with EU-INSPIRE;
- all the previous points favor landslide risk information and communication through public events to raise public awareness.

The application of the object-oriented and quantitative geomorphological mapping of landslides and related main landforms demonstrated that the approach to assessing the spatial and temporal relationships within landslides and affected slopes is very effective. This is true in the framework of interdisciplinary academic support to increase the governance capacity of institutions dedicated to disaster management and in the trans-disciplinary perspective of increasing public awareness and involvement of the non-academic institutions in strategic areas. Such areas are characterized by a high landslide hazard connected with strategic and spatially superposed infrastructures within the same narrow hillslope system (Strategic Infrastructure Corridor) at national and community level.

In conclusion, based on the discussed results, the combined analysis of TPI-derived features, process domains, and LOOM-based "eventories" could be an alternative method for assessing the landslide hazard, at least in similar landscapes. Such proposal is coherent with weak point v) of the risk management procedure, inserting in the Value Judgement and Risk Tolerance Criteria simplicity and effective interoperability in trans-disciplinary frameworks.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All the Authors contributed to the conceptualization and the drafting of the manuscript in equal proportion.

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Involving Risk Reduction Practitioners and Other Experts in the Management of Super-Catastrophes via an Online Interactive Platform

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Super-catastrophes that lead to extensive disruption and loss amplification are frequently due to domino effects crossing natural, technological, and socio-economic systems. Although secondary effects of natural disasters are often considered in official hazard assessment platforms (e.g., landslides following earthquakes, storm surges), the main catalysts of long chains-of-events, which are network failure and business interruption, are generally not. This is partly due to the difficulty in handling complex and systemic situations. Yet in an increasingly interdependent world, crisis management requires foresight with the ability to consider those secondary effects. Such an ability can be brought in using interactive numerical tools. We have developed an online interactive platform for the pre-assessment phase of super-catastrophes based on Markov chain theory. The tool is centered on the elaboration of a transition matrix of event interactions, from which domino effects can be modeled and ranked in the background. Risk practitioners and other experts first list hazardous events, which are then populated in the matrix in both rows (trigger events) and columns (target events). As the square matrix grows, the platform's users indicate which events can directly trigger another event in a binary approach. With enough participants, those binary decisions turn into weighted rules of interactions. In the process, the participants may discover missing links and update the matrix accordingly. To cover the full space of possibilities, three categories of events are systematically considered: natural, technological, and socio-economic. A group of experts can generate a transition matrix to explore the concept of super-catastrophe in general or to draw up possible crisis scenarios for decision-makers at any level of a territory (from a city to a country). Use of such a tool in practical situations, its integration into the management of prevention, planning for potential crisis situations, and training are discussed. Particular attention is given to the ability of this platform to help decision making within the context of a crisis unit with the need for quick evaluations.

Keywords: multi-risk, risk governance, risk communication, catastrophe dynamics, expert elicitation, crisis management

INTRODUCTION

Super-catastrophes, which lead to major economic losses and casualties (e.g., Shenhav, 1977), often result from the aggregated effects of connected disasters (Savy et al., 2008). The triggering chains of loss-generating events are often referred to as cascading effects or domino effects (Khan and Abbasi, 1998). Recent examples abound. The COVID-19 pandemic (e.g., Wang et al., 2020) triggered financial turmoil (Zhang et al., 2020), social unrest (Polo, 2020), psychological strain (Hou et al., 2021), and food insecurity (Barrett, 2020), among other domino effects. Other infamous super-catastrophes of the 21st century include the 2005 Hurricane Katrina, which produced a surge large enough to breach levees, ultimately triggering the flooding of New Orleans and cascading failures in numerous economic production sectors (Comfort, 2006; Hallegate, 2008), and the 2011 Tohoku, Japan, earthquake, whose unexpectedly high magnitude triggered a tsunami larger than what was planned in the protection of the Fukushima nuclear power plant, leading to a major nuclear accident with radioactive material released, along with other industrial accidents (Norio et al., 2011). This in turn led to the phase-out of civil nuclear energy in some European countries, whose full impact on energy security has yet to be fully understood.

Earthquakes, storms, and floods—some of the most devastating natural events on Earth—are particularly prone to triggering other natural events, critical infrastructure failures such as industrial accidents and lifeline ruptures, and further socio-economic disruption (Mignan & Wang, 2020). Worldwide, many other perils can lead to domino effects, such as epidemics and wildfires to only cite a few more. Man-made disasters directly triggered by malicious acts, malfunction, or human error (Chernov and Sornette, 2016) are more localized, but can also trigger numerous negative chains-of-events (e.g., Mignan et al., 2022).

Despite being among the highest-impact threats to our society, domino effects are often unforeseen as having been rarely experienced in the past. Mostly missing from historical records, complex domino effects may be referred to as downward counterfactuals (e.g., Woo and Mignan, 2018). Until recently, disaster risk reduction practitioners, decision-makers, and policy makers have treated natural and anthropogenic hazards separately. Although several hazards and risks may have been considered at the same time, spatiotemporal interdependencies have often been neglected (e.g., Schmidt et al., 2011 and references therein). This is understandable given the complexity of the processes involved and the compartmentalization of the expertise. Yet, the United Nations International Strategy for Disaster Reduction (UNISDR) is shifting towards a more dynamic, multi-risk approach to the problem (Aitsi-Selmi et al., 2016). This is urgently needed as our 21st century society is becoming increasingly complex and dependent on technology (Alexander, 2018). Many site-specific projects, often at the critical infrastructure or city levels, consider the multiple mechanisms leading to domino effects (Tang et al., 2019; Argyroudis et al., 2020). Stress test methods also include steps dedicated to the role of cascading effects (Esposito et al., 2020). However, there is no tool aimed at standardizing how complex interactions should be included and how to minimize the surprise effect of missing some critical interactions.

Multi-risk governance has recently been proposed as an extension of risk governance (Komendantova et al., 2014; Mignan et al., 2017; Scolobig et al., 2017). It first emphasizes the barriers related to the management of cascading effects, which are a lack of standardization and of cross-disciplinary expertise for multi-risk reduction planning, inadequate resources, and biases and barriers in communication between the relevant public and private actors, as well as between scientists and policy makers. It then suggests a multi-phase approach of observation (historical cases), social and institutional context analysis (via stakeholder engagement), generation of multi-risk knowledge (modelling), and stakeholder engagement processes (selection, implementation and evaluation of multi-risk management and reduction processes).

In this work, we present an online interactive platform for the pre-assessment phase of super-catastrophes. It is intended to be used by decision-makers and other domain-knowledge experts to brainstorm on the subject of cascading effects, to develop simple rules of event interactions in a qualitative to semi-quantitative manner, and to explore emergent chains-of-events in scenarios computed in the background using Markov chain theory. It brings together the first three phases of multi-risk governance, i.e., observation, stakeholder involvement, and modelling.

METHODS AND DATA

Catastrophe Dynamics Using Markov Chain Theory

Catastrophe dynamics, or the study of spatiotemporal interactions leading to complex catastrophic scenarios, can be modelled from Markov chain theory equations (Helbing & Kuehnert, 2003; Mignan & Wang, 2020) or via Monte Carlo simulations (e.g., Mignan et al., 2014, 2018; Liu et al., 2015; Matos et al., 2015). In both cases, a transition matrix encodes the conditional probabilities of possible one-to-one event interactions, from which scenarios of chains-of-events emerge. The Markov property simply indicates that the triggering of an event only depends on the last occurring event. The adjacency matrix $\boldsymbol{A}$ represents a convenient way to define hazard interactions (Gill & Malamud, 2014) and to display them in the form of a finite graph (e.g., Rocha et al., 2018). Each element $a_{i,j}$ of the square matrix of size $(n_{ev} \times n_{ev})$ represents the possibility, or not, of event j being triggered by event i for a total of n_{ev} possible events. An adjacency matrix can act as a transition matrix when the transition between two events (or two states) is defined by a conditional probability instead of a binary input. For sake of simplicity, we use the term 'adjacency matrix' in the main text of this article to refer to both the interaction graph and the transition matrix. We explain below how the conservation of probabilities can be enforced in the adjacency matrix.

Although simulations provide flexibility to also deal with non-Markovian processes (such as n-to-one interactions, long-term

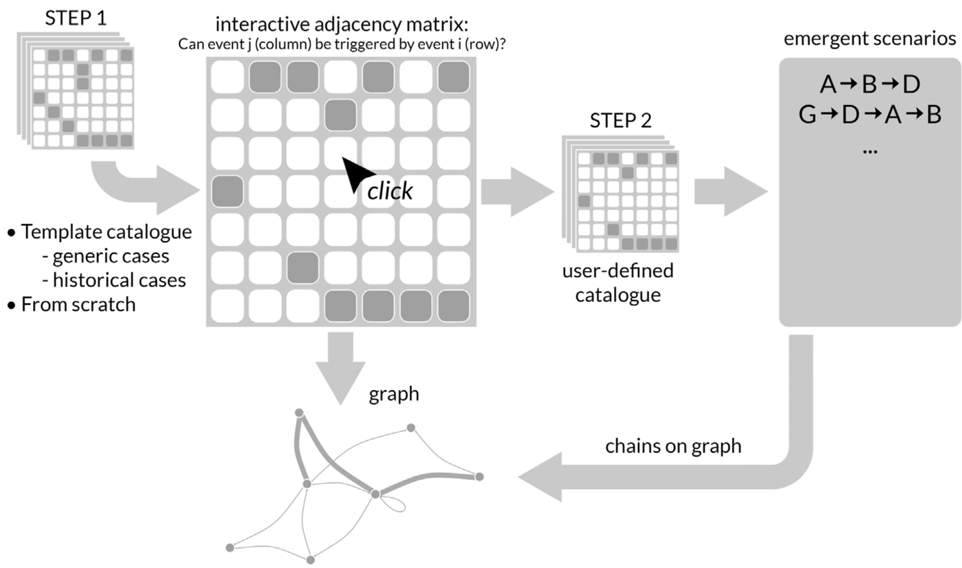

FIGURE 1 | Sketch of the online interactive platform for the pre-assessment phase of super-catastrophes. Emergent scenarios of domino effects are generated from the user-defined adjacency matrices and can be visualized on the resulting graph of interactions. See *Online Platform Prototyping* for details.

trends and seasonality, long-term memory), we here consider the much simpler case of memorylessness. A chain-of-k-events can then be encoded in the interaction matrix $\boldsymbol{M}$

$$\boldsymbol{M} = \sum_{\tau=1}^{k-1} \boldsymbol{A}^{\tau} = \boldsymbol{A} + \boldsymbol{A}^2 + \cdots \quad (1)$$

with τ the number of interacting steps (Mignan & Wang, 2020). In other words, if $\boldsymbol{A}$ encodes $1 \rightarrow 2$ and $2 \rightarrow 3$, $\boldsymbol{M}$ additionally describes the chain $1 \rightarrow 2 \rightarrow 3$. As τ increases, non-trivial patterns may emerge depending on the topology of $\boldsymbol{A}$.

In practice, we can estimate the probability of a chain-of-k-events $Z_k = (z_1, z_2, \cdots, z_k)$ using the Markov property so that $p_{Z_k} = \prod_{\tau=1}^{k-1} a_{z_\tau, z_{\tau+1}}$. The probability of a specific chain can then be ranked against all other chains-of-k-events (Mignan et al., 2022). Note that for the conservation of probabilities, an outflow event representing an absorbing state at which the cascade dies off must be added to the adjacency matrix (Mignan & Wang, 2020). This is, however, a technicality. An example of scenario generation will be given in *Scenario Development by User Elicitation: A Proof-Of-Concept*, with the conditional probabilities $a_{i,j}$ estimated by the weighting of binary adjacency matrices produced by the platform's users. The proposed approach is described below.

Online Platform Prototyping

The processes of catastrophe dynamics and their impact on super-catastrophe generation are described respectively by the adjacency matrix and ranked lists of chains-of-events, as defined in the previous subsection. The adjacency matrix can be displayed as a graph, and the chains-of-events as paths emphasized on that graph. We developed an online platform for super-catastrophe analysis based on expert elicitation, in which the adjacency matrix can be filled and expanded by the experts (i.e., the platform users). The matching interaction graph is then generated automatically and displayed alongside the square matrix of interactions.

Figure 1 illustrates the platform's concept. In a first step, prior to any input from the users, examples of chain-of-events encoding are provided to explain the concept. Those are listed in a catalogue of $\boldsymbol{A}$-templates. The users can then update those so-called templates, merge them, or create an adjacency matrix from scratch. A new graph is generated every time the encoding is modified. It is important to note that all those matrices have binary entries (interactions: yes, $a_{i,j} = 1$ or no, $a_{i,j} = 0$), which simplifies the user experience. A click on a cell $a_{i,j}$ allows one to change the class of that cell. In a second step, the adjacency matrices saved by different users to describe the same system are collated into a second catalogue of user-defined matrices. They are then weighted and used to generate scenarios of chains-of-events following Markov chain theory, which can be highlighted on the graph. Details about knowledge creation are given in *Assessing Event Interactions*.

Our platform is built with Python 3.9.0 on the Flask micro framework (https://flask.palletsprojects.com/). The platform relies on a couple of distinct elements to allow its versatility: the database of perils, interactions, and catastrophe models, and the application backbone handling data management and serving the web interface as well as some distinct graphical elements (the main one being the interactive adjacency matrix). Note that by catastrophe model, we mean the adjacency matrix associated with a specific scenario.

A SQL database hosts the data filled in the adjacency matrix by the users (see below). It is composed of distinct tables corresponding to the application data model: perils, interactions between perils, and catastrophe models. The three tables are connected as follow: perils are linked with interactions in two ways depending on whether they act as a trigger (or source) or a target and they can be part of multiple catastrophe models (i.e., individual matrices). Interactions have source and target perils which are taken from the peril table.

The application backbone is based on the micro framework of Python Flask. The core element of the backbone is the application model where perils, interactions, and catastrophe model objects are set. Communication between the application model and the database is relatively straightforward thanks to the Flask-SQLAlchemy module (https://github.com/pallets/flask-sqlalchemy). The basis of the web application is then built with Jinja Template Engine incorporated to Flask that enables the generation of HyperText Markup Language (HTML) files with embedded JavaScript (JS) and Cascading Style Sheets (CSS) for interactive plotting which is needed for presentations and online content (see some screenshot examples in *Results*).

The interactive adjacency matrix is made with D3.js which is a JS library for manipulating documents based on data (https://d3js.org/). Interactivity with users is made possible by some elements on the HTML page. The first one is the peril button which allows the user to add some new perils that are then incorporated into the matrix. Afterward, the user can create an interaction between two perils by clicking on the matching matrix cell. Finally, the Catastrophe Model Flowchart is dynamically built with Mermaid.js which is a JS based diagramming and charting tool (https://mermaid-js.github.io). Addition of further functionalities and changes in the design can be expected for future versions of the platform once user feedback has been received (see *Future Tests of the Platform*).

Assessing Event Interactions

The main purpose of the proposed interactive platform is knowledge creation for the critical and complex problem of catastrophe dynamics. Knowledge is created by the encoding of the adjacency matrix. In a first step, examples of encoded adjacency matrices are provided to the users. These include both generic cases and historical cases. Generic examples are used to illustrate the range of possible interactions, which are physically plausible and may occur at the macro-scale (Mignan & Wang, 2020) or micro-scale. By micro-scale, we mean the interactions that occur within an event, specifically in critical infrastructure failures (e.g., Matos et al., 2015; Mignan et al., 2022—see some examples below).

At the macro-scale, we consider the review made by Mignan & Wang (2020) which encodes interactions across natural, technological, and socio-economic systems. Considered events include earthquakes, volcanic eruptions, mass movements (landslides, rockfalls, avalanches, *etc.*), floods (river flooding, tsunamis, storm surges, *etc.*), windstorms (cyclones, tornados, *etc.*), other storms (rainstorms, hailstorms, lightning strikes, ice storms, sandstorms, *etc.*), extreme weather events (droughts, heat waves, frost, *etc.*), wildfires, epidemics, asteroid impacts, geomagnetic storms, fires, critical infrastructure failures (explosions, toxic releases, water releases, *etc.*), critical network failures (in transportation, water/gas/electricity supplies, cyberattacks, *etc.*), business interruptions, economic crises, social unrest, healthcare degradation, and conflicts (wars, revolts, terrorism, *etc.*). This example provides to the user an overview of a wide range of possible interactions.

At the micro-scale, we so far include a generic hydro-dam (Matos et al., 2015) which encodes interactions between the natural system and the elements of a hydro-dam. Here, some of the natural events are the same as above, such as earthquakes, floods, and landslides. As for the critical infrastructure failure, it is subdivided into subevents that characterize the micro-scale. Those are: bottom outlet failure, hydropower failure, spillway failure, reservoir rise, overtopping, and dam collapse. This example illustrates the complex interactions which are specific to one critical infrastructure type, indicating the need for domain-based engineering expertise. We plan to include, for example, generic cascades at nuclear plants (Ayoub et al., 2019) and historical cases of such failures, as what happened during the Fukushima disaster (Norio et al., 2011). All those examples are or will be recorded in a catalogue of adjacency matrices. How those examples are implemented and displayed on the platform is described in *Display of Generic and Historical Super-catastrophe Scenarios*.

In a second step, which corresponds to the core of the interactive platform, users fill the adjacency matrix individually. They can use a template from our catalogue, which may be one of the examples discussed in the previous paragraphs, or their empty counterparts where only the event list is kept but none of the interactions. Another option provided to the user is to build an adjacency matrix from scratch (**Figure 1**). For any option, events composing the matrix can be removed and/or others added, while interactions can be turned on or off, providing full control to the user.

As explained in *Online Platform Prototyping*, we offer a simple binary decision rule for the user: is the triggering of one event j by event i possible or not? User-defined adjacency matrices are saved within a second catalogue (**Figure 1**) and a merged adjacency matrix created with conditional probabilities defined as weighted sums of the results, $w_{i,j} = n_{i,j}/N$ where $n_{i,j}$ is the number of binary matrices with $a_{i,j} = 1$ and N the total number of matrices. This does not reflect the likelihood of the interaction in any physical sense, but rather the confidence of the experts that this interaction is possible. The resulting adjacency matrix can then be used to define and rank scenarios of chains-of-events (see *Scenario Development by User Elicitation: A Proof-Of-Concept*). To be consistent with the conditional probability $a_{i,j}$ defined in *Catastrophe Dynamics Using Markov chain Theory*, the sum of weights per trigger i must be smaller or equal to 1. We therefore define $a_{i,j} = \alpha w_{i,j}$ with α a proportionality factor chosen so that $\sum_{j=1}^{n_{ev}} a_{i,j} \leq 1$ and $a_{i,j} \ll 1$ since events are usually more likely to occur without triggering any secondary event when averaged over different environmental settings. The second condition also avoids exploding cascades.

RESULTS

Display of Generic and Historical Super-Catastrophe Scenarios

We defined several adjacency-matrix templates for the initial testing of our platform prototype. Some of the generic templates and the resulting interaction graphs are shown in **Figure 2**. It

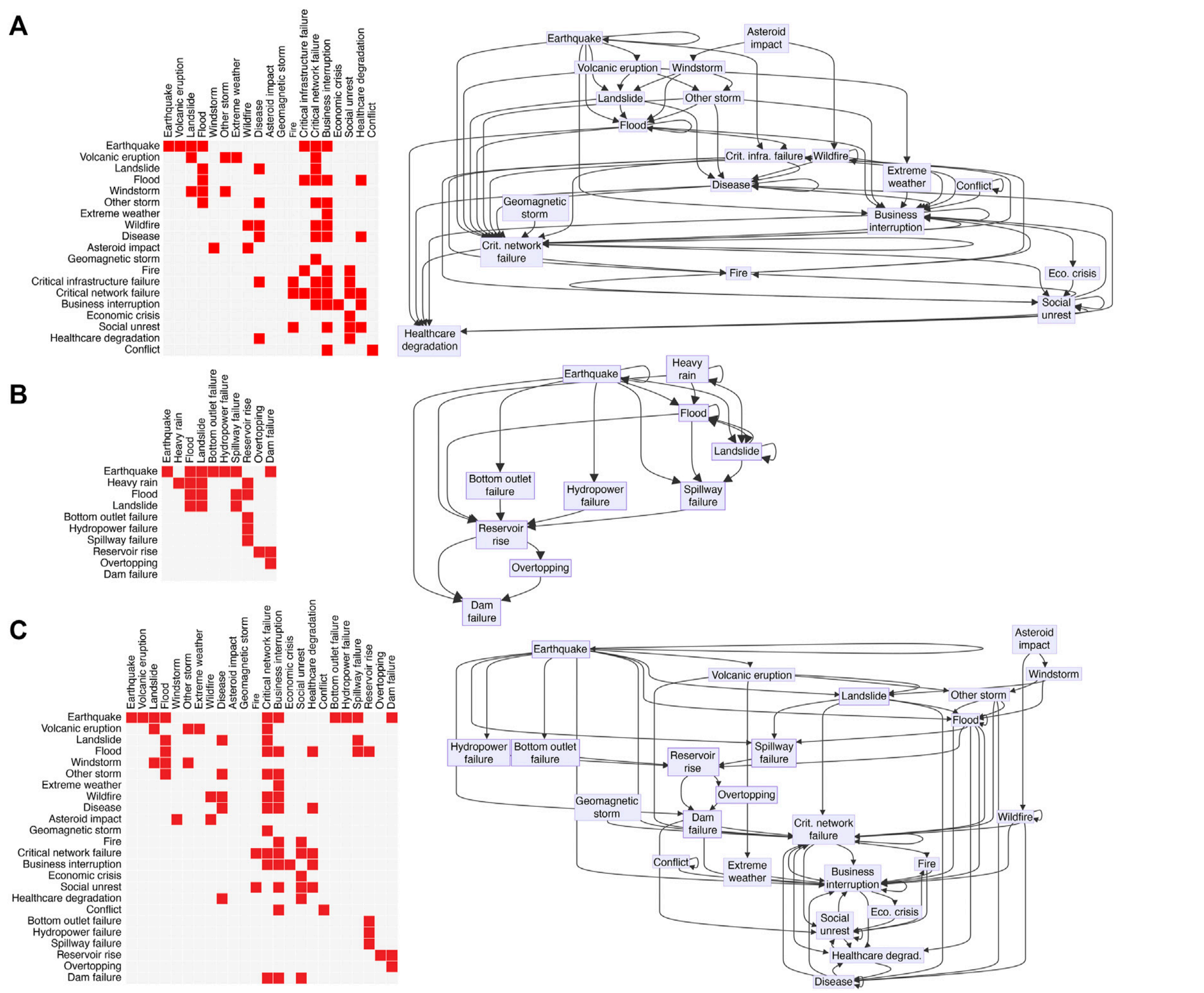

FIGURE 2 | Examples of generic adjacency matrices and matching graphs. **(A)** Generic interactions across the natural, technological, and socio-economic systems, globally (encoding from Mignan & Wang, 2020); **(B)** Generic interactions at a hydro-dam, a local critical infrastructure (encoding from Matos et al., 2015); **(C)** Interactions at both macro- and micro-scales merged into one adjacency matrix. All plots as screenshots from the prototype platform (with font size increased for the present figure).

shows that many one-to-one interactions, simple to individually encode based on a binary decision rule (*Online Platform Prototyping*), can rapidly combine into a complex web of potential chains-of-events. Often surprising scenarios emerge from such chains (see *Scenario Development by User Elicitation: A Proof-Of-Concept*). The power of the method is illustrated in **Figure 2C** where the generic macro- and micro-scale templates are merged into a meta-adjacency matrix that encompasses interactions at both spatial scales. While the operation is a trivial process that could be done in the background by the platform, it further increases the complexity of the interacting system. One can easily imagine encoding adjacency matrices for multiple types of critical infrastructures and combining them at the macro-scale of interactions. In practice, the two merged scales can represent the links between local critical infrastructure failures and their potentially greater consequences at the regional or national level when taking other loss-generating events into consideration.

Scenario Development by User Elicitation: A Proof-Of-Concept

Since the proposed platform has yet to be tested with decision makers and other experts (see future plans in *Future Tests of the Platform*), we here import the results of a session on reasoned imagination and cascading effects done in 2014 with natural science teachers (Mignan et al., 2016). Being part of a Swiss Seismo@School workshop, the focus was on earthquakes as primary triggers. The participants 38) were schoolteachers in natural sciences coming from 12 countries (Australia, France, Germany, Great Britain, Israel, Italy, Palestine, Portugal, Romania, Switzerland, Turkey, and the United States). The exercise lasted 1 hour and was in two parts: the participants

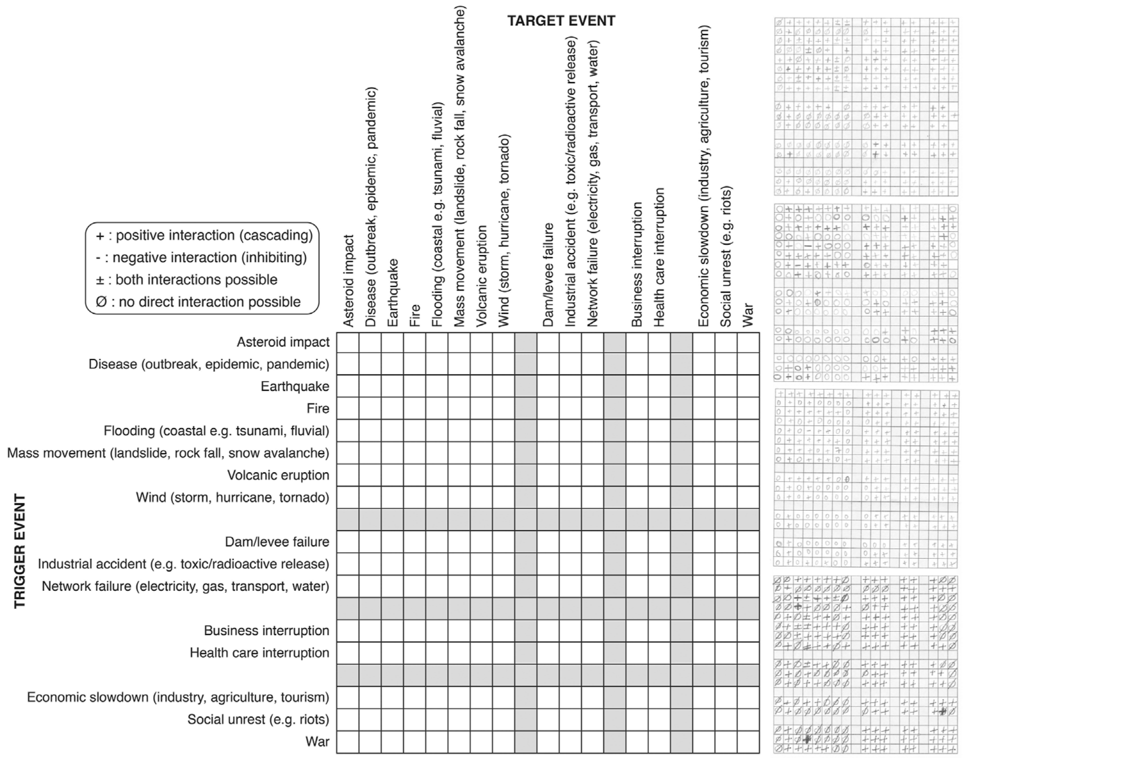

FIGURE 3 | The pen-and-paper exercise defined and tested in Mignan et al. (2016). Participants filled in the adjacency matrix shown on the left, indicating whether one-to-one interactions were possible (+, −, ±) or not (Ø). Three types of interactions were considered: triggering (+), inhibiting (−), and both (±). Four examples of filled adjacency matrices are shown on the right.

first listened to a seminar on historical cases of cascading effects, and then were asked to fill in an adjacency matrix based on what they previously learned as well as on their prior knowledge. To explain how to encode the matrix from chains-of-events to one-to-one interactions, 2 cells were filled during the seminar: ‘earthquake’ → ‘flood’ and ‘flood’ → ‘industrial accident’, representing a coarse-grained (or macro-scale) version of the Tohoku earthquake triggering the Fukushima nuclear disaster via coastal flooding (i.e., tsunami).

Two outcomes of that early study can be used for our present work, in addition to the original data. First, user inputs should be filtered so that unreliable adjacency matrices are removed. This was done by deleting any matrix where the two interactions described during the seminar had not been included. Mignan et al. (2016) showed that an improvement in the number of realistic scenarios arose after such filtering. Note, we have yet to define such filtering rules for the newly proposed online platform. Second, this exercise proved that users were able to define a large number of physically plausible interactions leading to emergent cascades not discussed during the seminar.

The 38 adjacency matrices of the 2014 pen-and-paper exercise (**Figure 3**) were digitized, making them equivalent to what the same users would have entered on the online platform. Of those, nine were removed by the filtering rule of Mignan et al. (2016). Considering the remaining 29 matrices for our user-defined catalogue, we defined a weighted matrix, which is shown in **Figure 4A**. We considered all the perils except asteroid impacts, which are extremely rare and would thus be overweighed compared to other triggers. Note also that three types of interactions were originally considered in the 2014 exercise: triggering (+), inhibiting (−), and both (±), as well as no interaction (Ø). Here, we combined (+) and (±) as $a_{i,j} = 1$, otherwise $a_{i,j} = 0$. We then defined conditional probabilities $a_{i,j} = \alpha w_{i,j}$ with $\alpha = 0.01$. We finally applied catastrophe dynamics to rank the most likely chain-of-k-events Z_k (see *Catastrophe Dynamics Using Markov chain Theory*) based on the users input, as shown in **Figure 4B** for $k = 5$.

The chains-of-events extracted from the exercise are mostly constrained by the historical examples presented during the seminar and cannot be considered representative of the true likelihood of chains-of-events. However, taken as a proof-of-concept, it shows how scenarios, getting more complex as k increases, can be generated from an adjacency matrix. We can expect that inputs from various experts considering a more constrained problem, such as interactions possible within a specific region or at a specific critical infrastructure, would lead to useful cascade information for further brainstorming in the phase of super-catastrophe pre-assessment.

Let us review the cascades shown in **Figure 4B** as they indicate some limits that will need to be addressed in future tests. The five most likely cascades contain the 3-event chain ‘earthquake’ → ‘flood’ → ‘industrial accident’ which was the one presented

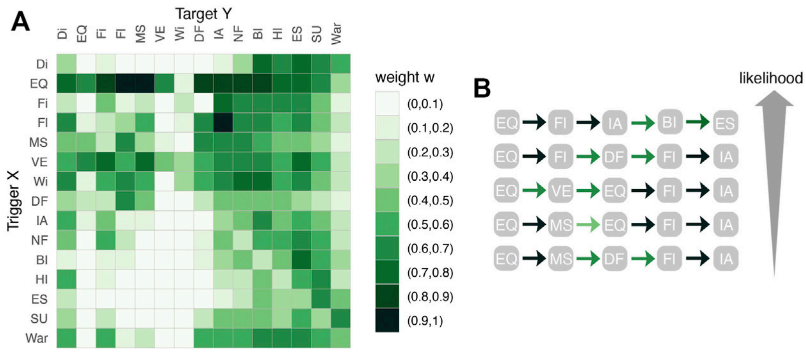

FIGURE 4 | (A) Weighted matrix based on participant input using the data from Mignan et al. (2016); **(B)** Top-5 chains-of-5-events modelled from the matching adjacency matrix (Di: disease, EQ: earthquake, Fi: fire, Fl: flood, MS: mass slide, VE: volcanic eruption, Wi: windstorm, DF: dam failure, IA: industrial accident, NF: network failure, BI: business interruption, HI: health interruption, ES: economic slowdown, SU: social unrest–following the nomenclature of Mignan et al., 2016). The top cascade derived from the present adjacency matrix is: an earthquake triggers a tsunami, which in turn leads to an industrial accident. It follows some business interruption and later some economic slowdown.

during the seminar, leading to some obvious overweight. In future applications, the impact of background information will have to be carefully assessed. Although it seems rather difficult to avoid the bias of historical events and background information from impacting decisions, aiming at the gradual development of a comprehensive and uniform database of interactions should limit overweighting linked to recent observations and fashionable trends. Moreover, two interactions proposed by the participants appear to be dubious: 'volcanic eruption' → 'earthquake' and 'mass slide' → 'earthquake'. Those interactions are highly unlikely if we mean a damaging earthquake of a relatively large magnitude. It is true however that both volcanic eruptions and landslides (or rock falls) can trigger micro-seismicity. This indicates that the problem of event scale (in terms of intensity, space, and time) is a critical aspect of catastrophe dynamics that will need to be considered. One solution would be to clearly fix the scales to be considered in cascade definition, for example, by only considering loss-generating events and to keep the resolution relatively coarse in a first stage. Users could also define intensity or damage thresholds to be considered for event selection and/or some bounds on the return period of primary triggers.

DISCUSSION

Crisis Situation Emulation

In a real crisis situation, crisis managers may need to consider different types of scenarios to make their decisions. Cascading events anticipated by the proposed platform may include planned-for events, or the crisis "automatic" responses already described in planification documents, as well as previously unplanned-for "surprise" events. Therefore, reference scenarios combining "surprise" cascading events and planned-for events may be presented to decision makers in addition to a limited number of optional crisis response scenarios.

It appears from presentations of this preliminary platform to decision makers (i.e., internal discussions at the Ministry of Energy, Transport and Ecological transition, Paris) that: 1) for the "situation picture" (i.e., a common crisis system description, including socio-economic sectors and actors' games), the platform first added value appears to be its ability to describe a complex situation involving several economic sectors and stakeholders and hence avoid or at least minimize silo effects; 2) dealing with complex situations, combinations of events lead to a very high number of possible scenarios, which has limited practical value to decision makers. Here, the platform's ability to identify a few relevant scenarios by a ranking strategy is an important outcome; 3) interviewees also stressed that interconnections between the suggested platform "situation picture" with implemented planification responses is essential for identifying where decisions must be taken.

The proposed online platform may have two implementation regimes:

- The matrix and scenarios are pre-filled and developed by experts from generic and historical data, crisis management plans, and exercise feedbacks during periods outside of crises. The objective here is twofold: (i) to get a comprehensive "theoretical" matrix at the national scale where interdependences are identified as possible; (ii) to define several relevant scenarios at the local level taking "in field" vulnerabilities into account.
- During crisis times, prefilled matrices are handled by dedicated crisis managers who complete and adapt the matrix with regards to the ongoing disaster's specific characteristics (e.g., unforeseen events and interdependences might occur which require scenario updating). They then release context-relevant scenarios and present them to decision-makers.

We believe that the work outside of times of crises is essential to have efficient and relevant scenarios during crises, but that it is not sufficient: adaptation to real events and data during a crisis is essential to make the platform's outcomes relevant to decision makers. During crises, we also believe that the platform can be used to train analysts who will fill in the matrix by themselves according to the situation and produce relevant scenarios for decision makers. This will require improvements in the platform for improved user experience, efficient input/output workflow, and proof of added value.

Future Tests of the Platform

We plan to test and enrich the proposed platform with crisis practitioners and experts within the context of two types of events, in crisis exercises and crisis laboratories:

Crisis exercises offer a double opportunity: on the one hand, they allow the testing of the platform's functionalities. Does it give an appropriate picture of the situation? Does it facilitate policy makers' understanding of the situation? Are the suggested crisis scenarios relevant to the situation? Answering these questions makes the functionalities more adapted to the crisis decision makers' needs. On the other hand, these exercises might be opportunities to fill the platform with data provided by participants. Indeed, the database development is the most critical aspect of the platform alongside the user interface. It will, therefore, require regular additions, analyses, and cleaning procedures outside of crisis periods and is crucial for good quality outcomes.

A "Crisis-Lab", or crisis laboratory, is a place where innovative crisis management tools are presented and discussed among developers and practitioners. At the Ministry of Energy, Transport and Ecological transition in Paris, for instance, there is a meeting every 2 months which aims to facilitate exchanges and make tools adapted to end users' needs. The current platform would benefit from this kind of workshop to gain feedback.

CONCLUSION

We have presented the prototype of an online platform for the pre-assessment phase of super-catastrophes based on Markov chain theory. The tool is centered on the elaboration of a transition matrix of event interactions (i.e., an adjacency matrix defined in terms of conditional probabilities), from which domino effects can be modeled and ranked in the background. The matrix can be pre-filled based on generic processes of peril interactions, or on historical disasters. Matrices can also be built and updated by users, and combined, analyzed, and used for brainstorming on the potential of complex chains-of-events.

The proposed online platform has yet to be tested with decision-makers, for either brainstorming sessions or in real crisis situations. Despite this current lack of feedback, we have shown from a proof-of-concept (**Figures 3**, **4**) how complex cascades and ranked chains-of-events could be generated based on user input. Although we used as data input from natural science teachers (Mignan et al., 2016), the underlying principle and process will remain the same when considering decision makers and scientific experts as participants.

A clear advantage of the online platform will be the added flexibility compared to the "frozen" proof-of-concept previously described. When a matrix is built from scratch or an existing matrix is updated (**Figure 1**), participants can list additional hazardous events, which are then populated in the matrix in both rows (trigger events) and columns (target events). Removing one event removes the matching row and column automatically. In the process of building the adjacency matrix and encoding it, the participants may discover missing links and update the matrix accordingly in a dynamic process. The essence of this flexibility was shown in **Figure 2** where two matrices at two different spatial scales were merged to produce a more complex system of interactions.

This platform needs to be further improved and updated based on future user feedback. Stakeholder workshops, as done in the past but at the time with pen and paper exercises (Komendantova et al., 2014; Mignan et al., 2017), will be required to fully identify the capabilities and usefulness of this new tool in crisis management.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

AM developed the concept, the model and wrote the original manuscript. LM developed the online platform. GD presented the method to decision-makers and provided potential user feedback. AM, LM and GD worked on the final version of the manuscript.

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DATA REPORT
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Developing an Open Database to Support Forensic Investigation of Disasters in South East Asia: FORINSEA v1.0

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INTRODUCTION

Arguably the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) fail to deal with root causes of disasters (Wisner, 2020) and therefore calls for science to support policy move towards more holistic solutions to disaster risk. In this context, root causes analysis has been described as "*a structured investigation that aims to identify the true cause of a problem and the actions necessary to eliminate it*" (DKKV, 2012, p. 12). A systematic review of 40 studies of disaster causation concluded that the FORensic INvestigations of disasters (FORIN) provides a broad and adaptable approach for the study of disaster root causes (Fraser et al., 2016). FORIN has been developed by the Integrated Research on Disaster Risk (IRDR) program of International Council for Science (ICSU), International Social Science Council (ISSC) and United Nations International Strategy for Disaster Reduction (UNISDR) (Oliver-Smith et al., 2016). The FORIN approach has been used to investigate the root causes of disasters around the world. For example, to reveal the underlying causes and risk drivers in the Haitian earthquake (Oliver-Smith et al., 2016), to inform the narratives to identify the factors that exacerbated the loss of human life in one of the most devastated local municipalities on the coast by 2011 Great East Japan Earthquake and Tsunami (Nakasu et al., 2017) or to understand the political ecology of the recurrent El Niño-related disasters in Peru (French et al., 2020).

FORIN research focuses on demonstrating with strong evidence that disaster risks are socially constructed. The principal contributing causes of disaster risk should be clearly identified along with ways in which they can be reduced or avoided through in-depth analysis that ties structurally-based root causes into causal chains to the active social drivers of risk that result in the unsafe conditions that place people in harm's way. There are two clearly differentiated stages in FORIN: "*FORIN analysis opts for a separation of basically descriptive, systematizing aspects of explanation from more deep-rooted causal analysis in order to organize thought and research needs as opposed to dictating an order of enquiry as such*" (Oliver-Smith et al., 2016, p. 23). The approach provides scope for flexible adaptation and application in different research contexts. This includes its application to complex phenomena such as climate change (Gotangco et al., 2014) and pandemics because the strengthened understanding of these socially constructed risks offers potential to "*move to a new and different normal, transforming the way the global geopolitics and economics are constructed*" (Alcántara-Ayala et al., 2021, p. 2).

The first FORIN descriptive explanation suggests the immediate relating of patterns of loss, damage and impact to the differentiated impact of hazards on exposed social elements. Vulnerability

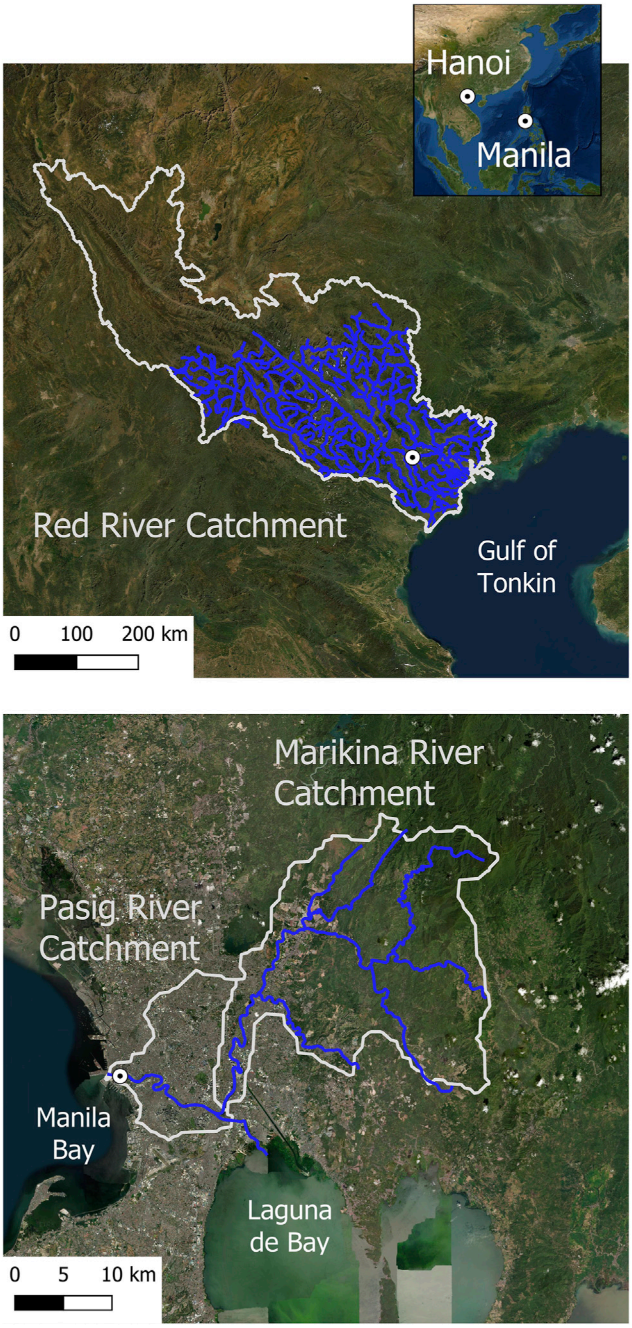

FIGURE 1 | For South East Asia region, we propose the use of hydrological catchment to define the boundaries of our human-natural system. The system contains a physical catchment that drains into the city (Hanoi and Manila), which continues to flow out to the coast or inland water reservoirs. Source of aerial imagery: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community, v10.6. Source of catchment area is the HydroBASINS layer (Lehner and Grill, 2013) from HydroSHEDS database. We have used modified layers at level 4 and level 8 for Hanoi and Manila study locations respectively. Source of river courses is the National versions of Vietnam and the Philippines from Global Map dataset (https://www.gsi.go.jp/kankyochiri/globalmap_e.html).

(and resilience) is a complex social condition often deriving from the workings and interaction of multiple dynamic processes and underlying "deep-rooted causes" (Oliver-Smith et al., 2016). The key areas of investigation to be developed at the descriptive level are: the triggering event(s), exposure of social and environmental elements, the social and economic structure of exposed communities, and institutional and governance elements. The FORIN guide provides no indication on how to systematically curate the data used for the descriptive research.

For South East Asia region, where flooding is the most frequent trigger of disasters (Doocy et al., 2013), we propose the use of the hydrological catchment as to define the boundaries of our system of analysis and to identify the main elements of our system. The physical (hydrological) catchment is an important element of the system, as its characteristics dictate the propagation of most types of hazard through the system. Other important catchments are defined by social and economic processes. For example, the movement of people in the search for work (largely in the city) defines a social catchment. Policies that initiate at the regional level may cross catchment boundaries. At the global scale, international trade deals clearly transcend catchment boundaries. This physical control vs. socio-economic processes may yield interesting insights. **Figure 1** shows the location of our two sites: 1) the Red River catchment (or parts of it) that drain toward and through Hanoi into the Red River delta; and 2) catchments that drain toward Marikina City and through the margins of the Manila conurbation. Each catchment site includes relatively large reservoirs that provide important processes related to water resources for agriculture, drinking water, energy, and flood control. Each site is subject to repeated typhoons and monsoonal rains, and is highly susceptible to mass movements of all types. Active faults are known to be present in both sites, although the background slip rates are likely very low (fractions of mm/y). Although we are largely concerned with hazards and their impacts that occur within the catchments, there are also hazards that can occur outside but that are large enough to have significant impact within the catchment. Earthquakes, tsunamis and volcanic eruptions are good examples. Even though these hazards are less frequent, they may figure more significantly in the culture of both people and disaster management authorities and therefore we cannot ignore them.

This article describes the development of a bespoke database, FORINSEA1.0, created to address the need for a systematic curation of information needed for the descriptive phase of the FORIN approach and its application to two study areas in the South East Asia region. FORINSEA1.0 allows researchers, for the first time, to explore and make use of subnational, geocoded data on major disasters triggered by natural hazards (flooding, earthquake, landslide and meteorological hazards) since 1945 until 2020 in the hydrological catchment of the Red River in Vietnam and the Marikina Basin in the Philippines. FORINSEA1.0 also contains relevant subnational information on relevant socio-economic policies and development of key infrastructure to provide the basis of the descriptive FORIN analysis. While the catchment approach is potentially

TABLE 1 | Variable overview and description included in FORINSEA v1.0: divided into hazard dataset and policy dataset.

Hazard	Name	Description
ALL	ab-nnnnn-ddmmyy-iiii a	country code (V = Viet Nam, P = Philippines) b = hazard type (F flood, L landslide, E earthquake, M met) nnnnn = 5 digits starting from 00001 for each hazard type ddmmyy = date of data entry iiii = initials of data enterer (up to 4 characters)
ALL	Official data	2 = government 1 = other official report 0 = other report
ALL	Location (name)	names of Barangay, Commune, District, etc.
ALL	Location (longitude)	Longitude as deg min sec
ALL	Location (latitude)	Latitude as deg min sec
ALL	Date started ddmmyy	starting from 1945, for example, 8/8/1945 will be encoded as 080845,.... 8/8/2020 will be encoded as 080820
ALL	Fatalities	number of people killed in that event, otherwise data will be encoded as “na”
ALL	People missing	the number of people missing in the event. If no data is available, it will be encoded as “na”
ALL	People affected	the number of people affected in the event. If no data is available, it will be encoded as “na”
ALL	People evacuated	the number of people evacuated during the event
F	Duration	the number of days the event takes place
F	Principal River Name	event area
F	Type of event	Type of event: i.e., if flooding event could be groundwater, pluvial, fluvial, or whatever local language words are appropriate
F	Related to named storm	Alternative names of the event
F	Directly incurred costs (USD)	Directly incurred costs in USD, if known
F	Indirectly incurred costs (USD)	Indirectly incurred costs in USD, if known
L	Landslide name/ID	Landslide name or ID if known
L	Landslide type	Landslide type if known
L	Volume	Landslide volume in m^3
L	Lithology	Lithology of a landslide mass
L	Main causes	Main causes of a landslide such as monsoon rain
E; M	Magnitude	E—Earthquake magnitude; M—precipitation event magnitude
E	Potential direct impact/damage to	Potential direct impact or damage
E	Potential secondary impact/damage to	Potential direct impact or damage
M	Precipitation event	Any details of a precipitation event
M	Typhoon	Name of typhoon (local name in parentheses)
M	Unnamed storm	Storm (any details of a storm)
M	Monsoon event	Any details of a monsoon event
M	Hail event	Any details of a hail event (local name in parentheses)
M	Rate of ppt (mm/hr)	Maximum if known qualified in Notes
M	Rainfall deficit	Maximum if known qualified in Notes
M	Other	Any other details
M	Temperature effect	Any available information on temperature effect
M	Temperature excess	Any available information on temperature excess
ALL	Notes	Any notes
ALL	References	Any available references

Field	Format	Description
Policy Dataset Vietnam		
Year	yyyy	Year of a document
Date of doc	dd/mm/yyyy	Date of a document
No. of Party Congress	1; 2;. . .	Number of Party Congresses
Ranking	1; 2; 3; 4; 5	1 = very unlikely; 2 = unlikely; 3 = possibly; 4 = likely; 5 = very likely
Socio- economic related content	Text	Document’s content
Viet-title	Text	Title in Vietnamese language
Eng-title	Text	Title in English language
Source	Text	Website of the policy documents
Policy Dataset Philippines		
Year	yyyy	Year of a document
Date of doc	dd/mm/yyyy	Date of a document
Title	Text	Name of a document
Presidential Decree/Republic Act/Batas Pambansa	Text	Type of a document (Act, order, plan, proclamation)
Ranking	1; 2; 3; 4; 5	1 = very unlikely; 2 = unlikely; 3 = possibly; 4 = likely; 5 = very likely
Source	Text	Website of the policy documents
Official Government website law repository URL	Text	Link to document

transferable to other regions, this Data Report does not show how these records might be applied or integrated to support a FORIN investigation of a specific disaster or event, neither provide basic ground rules for setting up similar systems in other countries.

MATERIALS AND METHODS

In FORINSEA1.0, all disasters are geocoded at subnational level with one row, or unique observation, per disaster event and affected area and all policy data (**Table 1**) are coded at different administrative level with one row, or unique observation, per the date and each observation including a link to the policy (and/or a citation), the keywords that are associated with it, the policy title and the and a qualitative ranking.[1]

Creating FORINSEA1.0 involved three main stages, explained in detail below.

Stage 1: Disasters and Policy Data Searches Criteria

In FORINSEA1.0 disaster dataset we limited our searches to the disasters triggered by the following natural hazards: flooding, earthquake, landslide and meteorological hazards. The different data sources were searched according to the keywords that the research team has agreed and considered relevant for the FORIN analysis. We did the search in three different languages: Filipino, Vietnamese and English. Filipino is the national language used as the medium of official communication and a language of instruction in the educational system. We also constrained the selection of triggering natural hazards to the Red River and Marikina river hydrological catchments. The Red River basin included nine provinces: Lao Cai, Yen Bai, Vinh Phuc, Phu Tho, Hanoi, Hung Yen, Ha Nam, Nam Dinh, and Thai Binh. For the Marikina river catchment study area we have included Region III (Central Luzon) that contains Angat Dam and Ipo Dam and Region IV (Southern Tagalog) where Wawa dam (decommissioned since the 1960s) is located. All these dams have provided water to Metro Manila.

In FORINSEA1.0 policy dataset we filtered for the policy database(s), guided by the overarching principle that policies of interest (relevance) includes policies related to forces, processes or events with potential to affect catchment attributes and dynamics (within the catchments and into Metro Manila or Hanoi):

1. Change land-cover or land-use
2. Change management of Flood Embankments Works (FEW) or other large infrastructure (e.g., highway construction)
3. Change/develop FEW/hazard infrastructure
4. Change the physical environment or its management, whether as part of DRR or climate change mitigation/adaptation, etc.
5. Agricultural and land-reform (forestry, mining, farming)
6. Change demographics (e.g., social housing policies, international trade deals, the Balikbayan program, etc.)
7. DRR related laws, regulations, etc.
8. Change political leadership that might result in more or less implementation of existing or future policies (e.g., changes in government party, or new leadership in national-local administrations).

A set of critical keywords were selected when searching the different policy data sources to filter the search by the above overarching criteria. The relevance to FORIN analysis ranking was done based on the time and geographical scope of the policy. For example, it is ranked as very likely relevant (rank 5) if the policy affected the land use within the Red River basin, and relevance ranked lower if the land used affected other provinces in the North of Vietnam (rank 4) or (rank 2–3) if land use affected other regions/provinces in South or Middle of Vietnam. Timewise, the policy data entrance is ranked higher (rank 4–5) if the land issues happened in the period of 1945 until 2020 and lower (rank 1–3) if plans are about land use in the future (2030–2050 for instance).

[1]Relevance to FORIN analysis ranked as: 1 very unlikely; 2 unlikely; 3 possibly 4; likely; 5 very likely.

Stage 2: Main Information Sources

Data has been collected from the following sources of information: easily accessible reports and articles, drawn from peer-reviewed literature, government and lending banks reports, disaster management reports, NGO reports, and open-library accounts.

For Vietnam, keywords used: land (use/reform/cover), land allocation for individuals/agencies, water management, waste management, manufacturing regulations, flood control, mining, deforestation, afforestation, fire-fighting, public health/public welfare, international trade deals, state/province financial management, town planning, social security for groups affected by natural disasters/land acquisition, disaster mitigation and risk reduction policies, population issues, social housing, agriculture policies, energy (oil/fuel/etc.), price/tax of land/housing, hydroelectric/dyke.

For the Vietnam policy dataset, the list of all policies from the National Database of Legal Documents (NDLD) was used which was available at the website until March 2020.

The data sources used for the Philippines includes Emergency Events Database (EM-DAT) (Guha-Sapir et al., 2014), scanned reports from the (previously called) National Disaster Coordinating Council (NDCC) and (presently called) National Disaster Risk Reduction Council (NDRRC) as well as scanned newspaper reports were obtained and used for the disaster dataset. In the Philippines, flooding as a hazard category is usually recorded under typhoons and not as an independent entity making it difficult to separate typhoon and flood events. Therefore, except for a few flooding entries from digitized newspaper sources and government records, most of the data entries for flooding were extracted from the global database, Emergency Events Database (EM-DAT). EM-DAT considers an event a disaster if at least one of the following criteria is met: 10 or more people dead, 100 or more people affected, the declaration of a state of emergency, and a call for international assistance. Under the Hydrological Disaster Subgroup, entries from EM-DAT were filtered to include only those under the Flood disaster type.

For the Philippines's policy dataset, we searched official government repositories of laws and policies. These would be from the Official Gazette and online libraries of the designated national government agencies which have mandates over specific areas of interest of the research. All laws are required to be published in the Official Gazette in order to become effective. Designated national government agencies are those identified under the law to lead in the management of specific areas of concern. Examples are natural resources and certain hazards are under the Department of Environment and Natural Resources, responding to hazards are under the National Disaster Coordinating Council/National Disaster Risk Reduction and Management Council, the Office of Civil Defence. While there are other private online law libraries these were referred to as auxiliary sources of information. The reason for this is that the completeness and accuracy of such documents are not assured by the website owners and are therefore not fully reliable. There has also been a period in Philippine History that many "midnight" policies were signed without going through the usual process of law making and policy formulation. Specifically, these occurred during the Marcos martial law period and during the presidency of President Joseph Ejercito (Erap) Estrada. Thus, we have relied mainly on what is contained in official online portals. A limitation of this research is that this was conducted during the COVID-19 pandemic. Ideally, the search should have covered printed materials from the Official Gazette (OG) and the Office of the National Administrative Register (ONAR). All executive/administrative policies become effective once submitted to the ONAR, and the ONAR issues regular printed publications of these policies. Not all volumes of the Official Gazette and the ONAR Bulletin are available online. Due to safety reasons and quarantine restrictions, our search has been purely on available online resources.

The keywords used were very similar to those used in Vietnam. These are: Settlement, Forest, Water, Water Management, Mining, Quarrying, Landslides, Climate Change, Renewables, Disaster Floods, Disaster, Flood, Emergency services, Drought, Famine, Evacuation, Migration, Typhoons, Earthquakes, Volcanoes, Lahars, Landslides, Agrarian Reform, Agriculture, Trade laws, Food trade, Disease Control, and Disease Surveillance. The Law Policy typology is based on whether the identified document is a law or an administrative regulation. Administrative regulations are policies which give detail to how the laws will be implemented. The type of law is also recognizable as belonging to a particular period in Philippine History. Since the period from 1945 to 1987 has been a period of transition from colonial to semi-colonial types of government, the lawmaking body has also shifted. During the Martial Law period, for example, the President had law-making powers. Under the 1987 Constitution, the law-making powers are lodged under the Congress. There were also laws passed during the American period which became effective even after 1945 and were changed only during the Martial law period. Thus, laws typology includes: Acts, Commonwealth Act, Republic Act, Presidential Decree, Presidential Proclamation, Batas Pambasa, Presidential Administrative Order, US Laws. The administrative policies typologies are: Presidential Letter, State of the Nation, Executive Order, Memorandum Order, General Memorandum Order, Letter of Instruction, Memorandum Circular, Proclamation, Administrative Order, Resolution, and Executive Agency Plan.

Lastly, these laws and policies have been ranked according to 1- Highly Unlikely to 5-Very Likely. This ranking is based on whether the law or policy, notwithstanding its content containing at least one (1) key word, is relevant to the study. The relevance is ranked based on whether this law/policy affects a) how the hazard is perceived by government regulators, b) increases or reduces vulnerabilities, and c) increases or decreases the exposure of vulnerable groups to the hazard.

Stage 3: Spreadsheet to SQL Conversion

The data were collected as Excel spreadsheets and these tables were reviewed to clean to transfer to PostgreSQL.

DATA RECORDS

The most notable characteristics of the natural hazards' events obtained for the Philippines and Vietnam study cases are summarized below.

The Philippines is hit by multiple typhoons every year and it is the most referred to meteorological hazard in the country. Hence, it is the hazard with the most data entries in this database. There is a total of 314 Typhoon entries in the database from 1951 to 2020; these range from tropical depressions to typhoons. Database columns that measure magnitude include 1) average wind speed and 2) rate of precipitation. However, the average wind speed values are not always given in reports and thus most data entries lack this. As for the rate of precipitation, this is not given in reports at all. Database columns that indirectly measure magnitude include 1) number of fatalities, 3) number of people affected. Entries in these data columns are more consistent and there are fewer missing values. Notable typhoon events are Typhoon Ketsana (Ondoy) of 2009 with a 110 km/h wind speed that caused 464 deaths and affected approximately 4,901,234 people. The Philippines was ill-prepared for a typhoon of this magnitude hitting Metro Manila, where the central government was located. This typhoon event eventually led to the creation of the new National Disaster Risk Reduction and Management Act of 2010. Typhoon Vamco (Ulysses) of 2020 is the most recent typhoon akin to Typhoon Ketsana. It caused 111 deaths and 4,945,461 people were affected.

Data entries for flooding events range from the year 1971 to 2016 with a total of 37 flood entries in the database. There are 12 entries before the year 2000 and 25 entries from 2000 to 2016. The flood of 7 July 1972 had the highest number of fatalities amounting to 427 with an approximate 6 million evacuees/people affected; it affected Central Luzon, Manila, and the Southern Tagalog Region. This flood was especially significant because it was 2 months before the declaration of Martial law by then President Ferdinand Marcos. In comparison, the recorded event with the lowest fatalities was on 17 January 2010 with only 1 fatality and 15,480 affected in Region IV.

There are 7 landslide entries ranging from the year 1971 to 2000. Database columns that indirectly measure magnitude include 1) People missing, 2) People evacuated, 3) People affected, and 4) Volume (of rainfall). However, most data entries are in the 3) People affected column, only one entry is included in the 1) People missing column and there are no entries in the 2) People evacuated column. Only one data entry, the Cherry Hills Landslide, included 4) volume of rainfall amounting to 4500 m^3 during the event. The most notable landslide event occurred on 3 August 1999, known as the Cherry Hills Landslide; it occurred in the Cherry Hills Residential Area in Antipolo, Rizal adjacent to Metro Manila. The landslide was caused by multiple nights of torrential rain and cause 58 fatalities and affected approximately 1,516,308 people. Even with multiple warnings people refused to evacuate due to not wanting to leave behind their belongings and believing their houses could withstand the landslide.

There is a total of 6 earthquake entries in the database from 1968 to 2018; 5 entries prior to the year 2000 and 1 entry during 2018. Database columns that indirectly measure magnitude include 1) Fatalities, 2) People evacuated, 3) People affected, 4) Potential direct impact/damage to, 5) and Potential secondary damage to. However, entries only usually have 1) Fatalities and 3) People affected. Moreover, data entries use different magnitude scales, but the Richter scale is the most consistently used (if any scale is given at all). Magnitude scales range approximately from 5.3 to 8.0. The 1990 Earthquake is the most prominent earthquake event in recent history; it affected Luzon wreaking most havoc in Baguio City (north of Metro Manila) with approximately 1,283 deaths and 1,255,248 people affected. This led to the re-examination of the National Building Code of the Philippines (NBCP) and the National Structural Code of the Philippines (NSCP). In 1992, the NSCP was revised and changes pertaining to anticipatory measures for soil liquefaction potential were introduced following the finding that the 1990 EQ damages were due to foundation failures due to liquefaction.

The most notable characteristics of the natural hazards' events obtained for Vietnam are summarized below.

Due to the geographical characteristics of Vietnam, storms and floods have a significant impact on the country. 455 flood occurrences, 104 landslide events, 44 earthquake events, and 187 storm events were included in the data collection. The information shown above was gathered from a variety of sources (national historical archives and NGOs authorized to operate in the territory). The data collection region includes the Red River Delta provinces, which now consist of nine provinces. As for the data collection period, we searched and filtered data from 1945 to the present, ensuring that all catastrophic events were within this time frame.

Because Vietnam is extensively hit by heavy rains every year, inundation data is the most reported of all the data obtained. It was gathered from 1941 to 2015. The number of individuals killed in the floods was not completely updated in all data entries. Aside from that, detailed records reports illustrate the flood's impact on dwellings, land, and agriculture. The data is stored in the form of documentation, and the local People's Committees create statistics and transmit reports in the form of official letters and orders to be saved in the national archives. In August 1971, a flood event occurred that was notable and had a significant impact on a vast region of the Red River Delta provinces. This disaster killed 100,000 people and devastated up to 4 provinces in the Red River Delta region. That flood was formed by a series of storms and torrential rain that lasted 26 days, from 20 July to 15 August 1971, and breached numerous critical dikes between 20 August and 27 August 1971. As a result, numerous regions were severely flooded and damaged.

From 1954 to 2020, there were 187 Hurricane listings in the database, ranging from tropical depressions to hurricanes. Columns in the Magnitude database include 1) average wind speed and 2) precipitation speed. However, mean wind speed measurements are not usually provided in reports, therefore most data items lack this value. Precipitation rates are not included in the reports. The database fields that quantify indirect magnitude are 1) the number of deaths and 3) the total number of people affected. These data columns' entries are more consistent and have fewer missing values. Storms in the Red River basin inflict minimal harm to humans, with yearly wind gusts ranging from 65 to 120 km/h. Storms in Vietnam's territory frequently bring severe rainfall, causing infrastructure damage and following events such as floods and landslides due to geographical factors. 4 successive storms occurred in August 1971, including JEAM, KIM, LUCY, and CORA, which occurred from July 18 in 1971, to August 28 in 1971, causing significant flooding.

Between 1990 and 2015, there were 104 landslide entries. Columns in the indirect intensity measurement database include 1) Missing People, 2) Evacuated People, 3) Affected People, and 4) Volume (precipitation). Most of the data entries, however, are in column (3) Affected Person, with just one record in column (1) Missing Person and no entry in column (2) Evacuated Person. Because Vietnam's geography is hilly, landslides that caused significant damage occurred in provinces such as Yen Bai, Lai Chau, Bac Kan, Son La, Tuyen Quang, and Ha Giang.

Vietnam is not located on the world's seismic belt; reported earthquakes are in the range of magnitude from 4.1 to 6.9 over a short period of time. As a result, earthquakes on Vietnamese territory were reported with minor damage to infrastructure and no loss of life. From 1945 through 2018, the database contains 44 earthquake entries. The database columns that indirectly measure magnitude include 1) Deaths, 2) Evacuated Persons, 3) Affected Persons, 4) Potential Direct Impact/damage to, 5) and Potential Secondary Damage. However, the entries are usually only (1) Deaths and (3) Affected Persons. Furthermore, the data items use different magnitude scales, but the Richter scale is used most consistently (if any). The magnitude scale ranges from 4.1 to 6.9.

TECHNICAL VALIDATION

FORINSEA1.0 was developed by undertaking an extensive search of documentation from a variety of readily available digital and paper-based data sources. We now outline a number of methodological issues encountered in the process of compiling the database.

A central challenge when working with geographical data relating to historical events is temporal bias in coding. Information about natural hazards and resulting disasters is much more readily available today than in the 1940's, and this is especially true regarding details on the location of remote events in developing countries. However, the increasing frequency of disaster events is also due to two other contemporaneous trends: global warming and associated physical processes that have increased the prevalence and severity of natural hazards, and population growth and shifting settlement patterns that have led to increasing human exposure to several types of hazards.

For the Philippine's disasters dataset, most reports from government agencies were obtained as scanned documents. This made the task of looking through hundreds of pages for necessary data a difficult and slow process. Moreover, duplicate entries from EM-DAT were meticulously checked and replaced with local sources, since national-level reports take precedence.

Location information on disaster events from EM-DAT mostly makes use of first-order or second-order administrative levels (i.e., for the Philippines, regional and provincial level). However, some entries use third-order administrative levels (i.e., city/municipal) or even refer to the country's main island groups (i.e., Luzon, Visayas, Mindanao) thus making location information inconsistent. The flood entries were then delineated to only include adjacent regional-level locations (i.e., Region III and Region IV) to the project's area of interest, Metro Manila or the National Capital Region. This delineation could be compared with the Geocoded Disasters (GDIS) dataset (Rosvold and Buhaug, 2021) which provides spatial geometry in the form of GIS polygons and centroid latitude and longitude coordinates for each administrative entity listed as a disaster location in the EM-DAT database.

Database columns that measure magnitude of tropical cyclone disaster subtype within EM-DAT include 1) Average wind speed and 2) rate of precipitation. However, the average wind speed values are not always given in reports and thus most data entries lack this. As for rate of precipitation, this is not given in reports at all. Database columns that indirectly measure magnitude include (1) number of fatalities, (3) number of people affected. Entries in these data columns are more consistent and there have fewer missing values.

USAGE NOTES

FORINSEA1.0 provides a comprehensive and coherent historical record of disasters, from 1945 until 2020, socio-economic policies and development of key infrastructure at the hydrological catchments of the Red River Delta in Vietnam and the Marikina river basin in the Philippines. The FORINSEA1.0 dataset allows researchers, for the first time, to explore and make use of geocoded data on major disasters affecting the two large and rapidly expanding cities of Hanoi and Metro Manila and their catchment areas. This dataset is the result of an international collaborative effort to support the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR). The catchment approach used for the creation of this dataset is potentially transferable to other regions and we have illustrated how different global datasets (e.g., HydroSHEDS and EM-DAT) can be combined with other in country data sources to create an inter-related set of evidence suitable for FORIN descriptive explanation phase.

DATA AVAILABILITY STATEMENT

FORINSEA1.0 is available for the public to download in the online Zenodo (2022) repository with DOI: https://doi.org/10.5281/zenodo.6200644. The dataset is stored in two different formats; as Comma Separated Values (CSV) format for ease of use in any statistical software, as PostgreSQL (SQL) for use with open PostgreSQL software. The multi-hazard-event database is also available as a SHAPEFILE (SHP) for use on Geographical Information System (GIS).

Additionally, the FORINSEA1.0 dataset can be queried via the British Geological Survey data Centre portal following the steps indicated below:

1. Download PGAdmin4 from here: https://www.pgadmin.org/download/
2. Go to Object >> Create >> Server
3. In the General tab, give the server a name such as 'Multihazard'
4. In the Connection tab, enter:
   a. Host name/address: 194.66.252.166
   b. Port: 5432
   c. Username: MHZdb_Read
   d. Password: mult1HzR2ad
5. In the left-hand panel you can now navigate your server: Multihazard (or whatever name you gave it) >> Databases >> MHZdb >> Schemas >> multihazard >>Tables
6. Right click on the EVENT table and select View/Edit Data >> All rows
7. Scroll all the way to the right, the last column called 'geom' and click the eye icon to preview the map

Figure 1 incorporates data from the HydroSHEDS database which is © World Wildlife Fund, Inc. (2006–2013) and has been used herein under license. WWF has not evaluated the data as altered and incorporated within Figure 1, and therefore gives no warranty regarding its accuracy, completeness, currency or suitability for any particular purpose. Portions of the HydroSHEDS database incorporate data which are the intellectual property rights of © USGS (2006–2008), NASA (2000–2005), ESRI (1992–1998), CIAT (2004–2006), UNEP-WCMC (1993), WWF (2004), Commonwealth of Australia (2007), and Her Royal Majesty and the British Crown and are used under license. The HydroSHEDS database and more information are available at http://www.hydrosheds.org.

AUTHOR CONTRIBUTIONS

Conceptualization, AP, MG and YH. Methodology, AP, MG and YH. Software, AB and JM. Validation, AG, PD and YH. Formal analysis, AG, PD and YH. Writing—original draft preparation, RA and AP. Writing—review and editing, AP, RA, AG, PD, and YH. ALL authors have read and agreed to the published version of the manuscript.

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Assessing and Managing Risk in Historic Urban Areas: Current Trends and Future Research Directions

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Historic urban centres are, almost by definition, risk-prone areas. The buildings in the historical sites are often highly vulnerable to natural and human-made hazards, not only due to their construction and material characteristics but also because they are usually very degraded due to ineffective maintenance and conservation policies. Moreover, the recent world tourism boom has led to a significant increase in the number of people who live, work and visit these areas, which, together with land use and climate change-related impacts, make historic centres particularly exposed areas. This paper addresses the issue of assessing and managing risk in historic urban centres departing from the complexity of defining the historic city and the concept of risk, providing a comprehensive discussion on current trends and future research directions in this field. After analysing the most suitable methodologies to assess the vulnerability of these areas to different hazards, the focus is on data collection and organisation-related issues and how the different vulnerability assessment outputs can be used to manage and mitigate risk. Vulnerability and loss scenarios, evacuation and emergency planning, and retrofit and cost-benefit analyses are some of the aspects addressed herein. This discussion includes some considerations on the accuracy of these approaches and aspects related to their calibration and validation, covering from empirical calibration models to advanced artificial Intelligence-based techniques.

Keywords: risk assessment, seismic vulnerability, fire risk, flood risk, historic urban areas

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1 INTRODUCTION

Urban areas are, by definition, highly vulnerable to natural hazards (Ferreira et al., 2013). The cities are physical places where several actors, stakeholders, assets and activities converge. In particular, the long-term processes and transformations of the historic centres result in a wide variety of uses and unique configurations. These singularities, which are often a manifestation of cultural values, also demand a very specific and straightforward analysis of the historic city and the challenges it must face, such as risks associated with natural hazards. The impact of certain disastrous events—including those commonly named as natural disasters (Chmutina and von Meding, 2019)—brings a series of irreversible consequences, such as human and economic losses and the destruction of irreplaceable architectural and cultural heritage. Then, it becomes relevant to promote sustainable development and resilient communities towards risks.

A recent United Nations report (United Nations Office for Disaster Risk Reduction, 2018) focused on the 1998–2017 period, concludes that floods (43.4%), storms (28.2%) and earthquakes (7.8%) are three most significant hazards in terms of recurrence. However, when unfolding these figures, it is possible to observe that the proportion of people affected by each of these hazards is significantly different—56% of human casualties are related to earthquakes, 11% to floods, and 17% to storms. A similar dissonant trend can be observed when analysing economic losses. For the 1998–2017 period, storms were responsible for about US$ 1,330 billion in losses (46% of the total amount of economic losses recorded), whereas earthquakes and floods were responsible for about US$ 655 billion each. The impact of natural hazards on heritage, particularly in World Heritage sites, has also been analysed by (UNESCO, 2007) in several case studies, in an attempt to identify possible combinations of factors (location, uses, external events, etc.) that can lead to the development of damage and decay processes in historic cities.

Besides natural hazards, man-made phenomena can also negatively affect historic cities. Wars are an archetypical example of this, damaging or completely destroying several cultural heritage sites every year. Although much discussion has been done on this topic after World War II (Moustafa, 2016), the difficulties in protecting cultural heritage in war contexts is still a real issue today, as is, for different reasons, the increasing pressures resulting from mass tourism, real estate speculations and gentrification (García-Hernández et al., 2017). These phenomena are worldwide spread and have contributed to a significant loss of heritage value and identity.

The risk analysis for historic urban areas must encompasses a series of conceptual frameworks, mostly related to the urban components and their functions. There are some interesting efforts towards framing historic cities in generalised and comprehensive structures, such as the so-called Historic Urban Landscape (HUL). This concept is the core of a systematic framework for studying urban phenomena. The HUL Guidebook developed by UNESCO (2016) proposes a series of strategies for assessing and planning more sustainable historic cities. The implementation of the HUL approach is still a relatively novel field, namely due to the complexity of conciliating the interests of numerous agents. Some experiences, however, are aimed to propose holistic and comprehensive strategies in which cities can be understood by means of models, diverse characterisations and semantic descriptions (Angrisano et al., 2016; Rey-Pérez and Pereira Roders, 2020; Ramírez Eudave and Ferreira, 2021a).

One of the most important steps of the HUL approach consists of assessing the vulnerability of the city towards natural events, socio-economic stresses and climatic change. In this context, it becomes determinant to anticipate the challenges that a city will reasonably face, compromising its functions, material assets, inhabitants and immaterial values. Some estimative on this field express the proportion of the long-term impact that these events would have. For example, the Financial Risk and Opportunities to Build Resilience in Europe inform (World Bank, 2021) states that major disasters create liabilities that can exceed 17% of Gross Domestic Product in European countries. Furthermore, it presents a scenario in which there is a 10% chance of having an earthquake or flood that will exhaust the existing finance. Preparedness towards these scenarios is a key for guaranteeing the sustainable future of historic cities.

In this framework, the present manuscript provides a compilation and discussion of research focused on the assessment of the vulnerability and risk in urban areas to natural and human-made hazards, including earthquake, fire and flood. By covering a wide range of approaches and research experiences, such a review is mainly targeted to researchers, practitioners and decision-makers interested in a broad but integrative approach to the topic.

2 PROACTIVITY TOWARDS URBAN RISKS: UNDERSTANDING FOR ANTICIPATING

Risk awareness in historic cities should start with establishing the perturbations imposed by the events and the sensibility that the systems and components of the city have towards them. It is relevant to understand the performance conditions of the city (i.e., its functions and the elements that sustain them) and their association with mechanisms of perturbation, being, in this sense, convenient to start this discussion by exploring the concept of risk and its components.

2.1 A Brief Literature Review

Literature devoted to characterisation, assessment, and mitigation of urban risks is vast due to the wide variety of environments, hazard sources, and approaches. For this reason, any attempt to put together and discuss the literature on this topic is doomed to failure. Even so, it is essential to mention in the context of this paper a few works that, thanks to their groundbreaking nature, have shaped the current knowledge in this field. The description of the city is still an open discussion in which the vision of diverse stakeholders can determine how the city is understood. For example (de Carvalho et al., 2019), discusses how the vial networks of city centres are seen and perceived from different agents, such as residents, retailers and carriers. This work schematises the relations existing among decision-makers, logistic operators and users by putting together a series of mixed indicators and interests in which there is a shared responsibility and/or impact: Air quality, induced damage on historical constructions, economic prosperity, visual impact, productivity, safety, etc. This work emphasises the need to involve agents that are often considered out-of-scope to assess the vulnerability of cultural assets and the historic urban landscape. Furthermore, these authors explore a multi-criteria structure based on economic, environmental, social, operational and cultural factors for deciding the most suitable location of distribution facilities based on its impact on diverse aspects of the historical city, from architectural impact and visual pollution to local gains.

Another example of a comprehensive approach for assessing the impact of implementing energy-conservation measures in historic urban areas was recently proposed by (Egusquiza et al., 2018). In this work, the authors resort to the concept of Heritage Impact Assessment (HIA) to assess the invasiveness and impact that specific actions have at the level of a component, building or district. Most of the impacts considered are related to changes in the visual environment, which reflects a relevant issue when working on protected areas of cultural interest. Among other relevant aspects, this analysis emphasises the need for having multi-criteria and comprehensive frameworks for assessing enhancement actions, such as those related to energetic efficiency. Furthermore, this multi-scale analysis can be scaled and transposed to other phenomena, including the seismic vulnerability assessment of historic cities.

As discussed by (Julià and Ferreira, 2021), the use of multi-criteria and multi-risk assessment approaches is fundamental to get a proper contextualisation of the city towards complex and mixed events. The effects of climate change are an illustrative example of this. The work of Quesada-Ganuza et al. (2021), for example, provides a literature-based identification of the link between risk, vulnerability and systems-related aspects that interact in the context of complex climate-change-related events. Besides the multi-criteria comprehensive assessment, Coletti et al. (2020) explores another utmost important aspect in this context, time-dependency, discussing the plausibility of risks according to the evolution of the levels of risk over time. This approach is based on both quantitative and qualitative inputs, which are then used to feed a geographical information database. The outcomes of this analysis present time-dependent scenarios associated with urban functions along the day, assembling a synergic and more detailed risk analysis framework.

2.2 Risk: A Challenging Concept

A complete description of risk must include the likelihood, nature and behaviour of the hazard, the sensitivity that the systems or components of the city have towards the hazard, and the elements that are or can be exposed to damage or loss. There is a minimum set of concepts for approaching any kind of risk. A general and comprehensive conceptual framework is given in the international standard ISO 31000, which offer a series of principles and guidelines for risk management (International Organization for Standardization, 2006). This standard covers all the conceptual basis, from the identification of the risk processes to risk management, mitigation and acceptability. Moreover, several international documents comprehensively address the concept of risk in the context of natural events; the most significant of those are probably the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015). Still in this context, a robust state-of-art review on scientific risk management has been consolidated by the Disaster Risk Management Knowledge Centre of the European Union (Poljanšek et al., 2017).

Generally speaking, risk can be understood as the "uncertainty of achieving objectives due to external factors and influences". Although this definition is particularly tailored to organisations, it is suitable for analysing almost any organised system, such as urban entities. Considering that the basic premise of a city is to ensure a series of financial, health, safety, environmental and even cultural functions. In that case, the first approach of risk in the context of a historic city is the uncertainty of achieving these functions as a result of external factors and influences, including disruptions and performance diminution. Those functions can include issues as diverse as housing, transit, commerce, leisure, culture, education, etc. From this risk definition, ISO 31000 standard suggest a series of concepts such as:

- Risk evaluation: Process of comparing the results of the risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable according to the predictable consequences and the admissible perturbations on the urban functions.
- Risk criteria: Terms of reference against which the significance of a risk is evaluated.
- Risk source: The element that, alone or in combination, has the intrinsic potential to give rise to the risk.
- Event: The occurrence or change of a particular set of circumstances.
- Consequence: The outcome of an event affecting objectives.
- Likelihood: The chance of something happening.

Mathematically, risk (R) can be understood as the product (or confluence) of a hazard, i.e., an event that changes a set of circumstances (H), the vulnerability of the city towards the changes imposed by the hazardous event (V), and the elements that are exposed to damage or loss as a consequence of the event (E): $R = H \otimes V \otimes E$ (Maio et al., 2018). This qualitative expression can and has been used to frame diverse types of hazards, vulnerability and exposure. The historic city can be read from many points of view, but a very common strategy is to conceptualise it as a configuration of the built space (i.e., taking buildings, infrastructure and anthropic assets as the configuration elements of the city). This codification of the city results useful for determining schematic models that are helpful for understanding the city as a functional organism with interdependent uses, activities and components.

A feasible approach for the functional characterisation of the historic city is the Failure Mode and Event Analysis (FMEA) approach (Shamseddin Alizadeh et al., 2015), which starts from the identification of the subsystems and components of a general system (i.e., the historic city). These subsystems and components are described, including their functions and interactions among subsystems (e.g., the dependencies). Each subsystem is associated with a set of performance requirements (i.e., the agents that sustain the functions of the subsystem) and a set of potential failure modes, usually known as disruptive events or situations. Each failure mode is analysed on its root causes and effects (in the short, medium and long term). Furthermore, the means and methods for detecting the root causes are established, supporting a set of mitigation measures. This approach can be extended and complemented with other analysis tools, such as Failure Tree and Event Tree Analysis, which are specifically aimed to analyse a chained series of events that trigger or are triggered a determinate failure Ramírez Eudave and Ferreira (2021c).

2.3 Main Risks in Urban Areas

It is possible to list a wide variety of relevant hazards associated with the historic city. From those, earthquakes, urban fires and floods have proved to be particularly meaningful due to their impact on buildings, infrastructures and people. In the context of risk and its components, engineering can promote actions for mitigating and reducing the vulnerability of constructions and infrastructure towards these hazardous events. Nevertheless, any intervention must frame hazards in descriptive metrics for

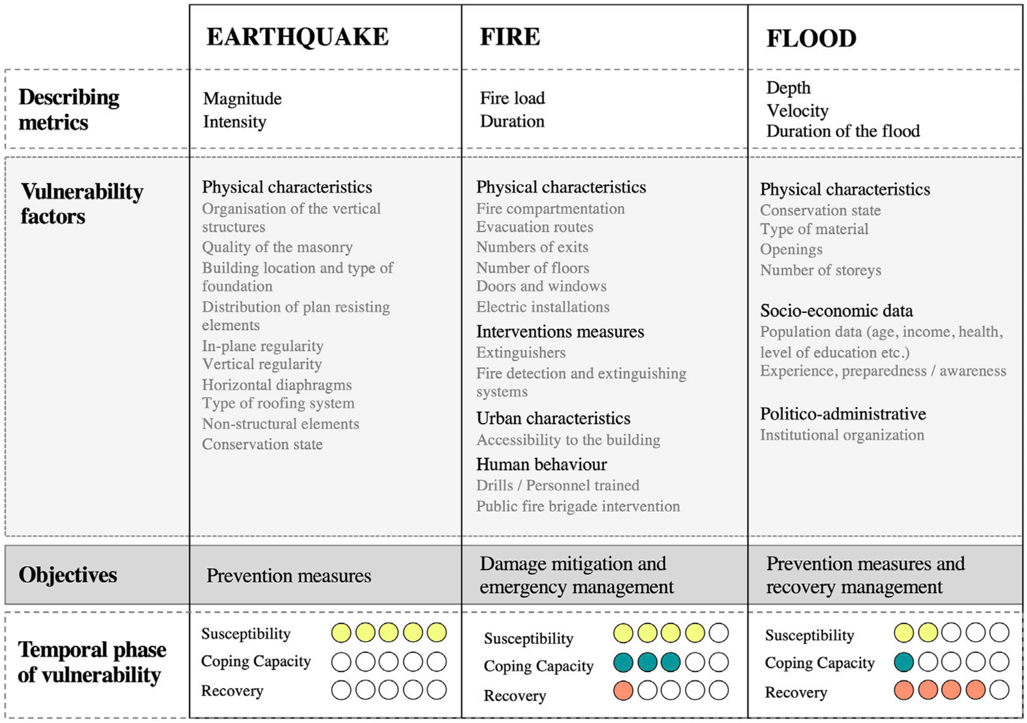


FIGURE 1 | Earthquakes, fire and flood as hazardous events for buildings and infrastructure.

measuring their magnitude and impact, identifying the parameters that influence the most the vulnerability of buildings and infrastructure, and, finally, paving the road for mitigating the adverse effects of those event. **Figure 1** summarises the three most frequently used descriptors for analysing earthquake, fire and flood risk in urban areas: the metric for measuring the intensity of the event, which can be qualitative, quantitative or semi-quantitative; the vulnerability of the built environment; and the ultimate objective of the analysis in terms of prevention measures, damage limitation, and post-event recover. It is worth noting that, although these descriptions are associated in **Figure 1** with earthquake, fire and flood hazards, they are representative and be used to guide risk analyses for other hazard sources.

3 DATA-ACQUISITION STRATEGIES AND ASSESSMENT METHODOLOGIES

According to the HUL approach, consequent risk assessment depends on a representative characterisation of the historic city and, therefore, an adequate data-acquisition approach. A phenomenon can often be assessed and characterised with different approaches and resolutions. As an example, the seismic vulnerability of a building can be measured by resorting to simplified parametric-based procedures, for which a relatively small amount of input data is required, or using highly complex computational models able to simulate the dynamic behaviour of the structure. As comprehensively discussed in Ferreira et al. (2019), the selection of the approaches depends on the availability of resources. The type of approach to use and the way how it will be implemented are two aspects that must be considered carefully before carrying out any assessment.

3.1 Data-Acquisition Strategies: Scales and Tools

One of the most critical challenges in this context is the need of performing observations in different scales for assessing a phenomenon. For example, a comprehensive assessment of the fire vulnerability of a building should include not only specific details of the structural features of the building but also territorial-scale characteristics, such as water availability and distance to firefight infrastructures. This need to acquire multi-scale data from the city makes it essential to use complementary tools and approaches for covering specific scale-related requirements.

Acquiring data in existing buildings usually involves carrying out fieldwork and visual inspection. One of the most common strategies for supporting on-site inspections is to organise the descriptors of the surveyed entity in a datasheet. Among other practical advantages, these datasheets facilitate gathering all the data required for the assessment in an organised and methodological manner. It is important to remark that the design of the survey sheet may compromise the success of the work, and thus datasheets should be clear, straightforward, and tailored to the specificities of the buildings to be assessed. In fact, the selection of descriptors is another crucial aspect to get

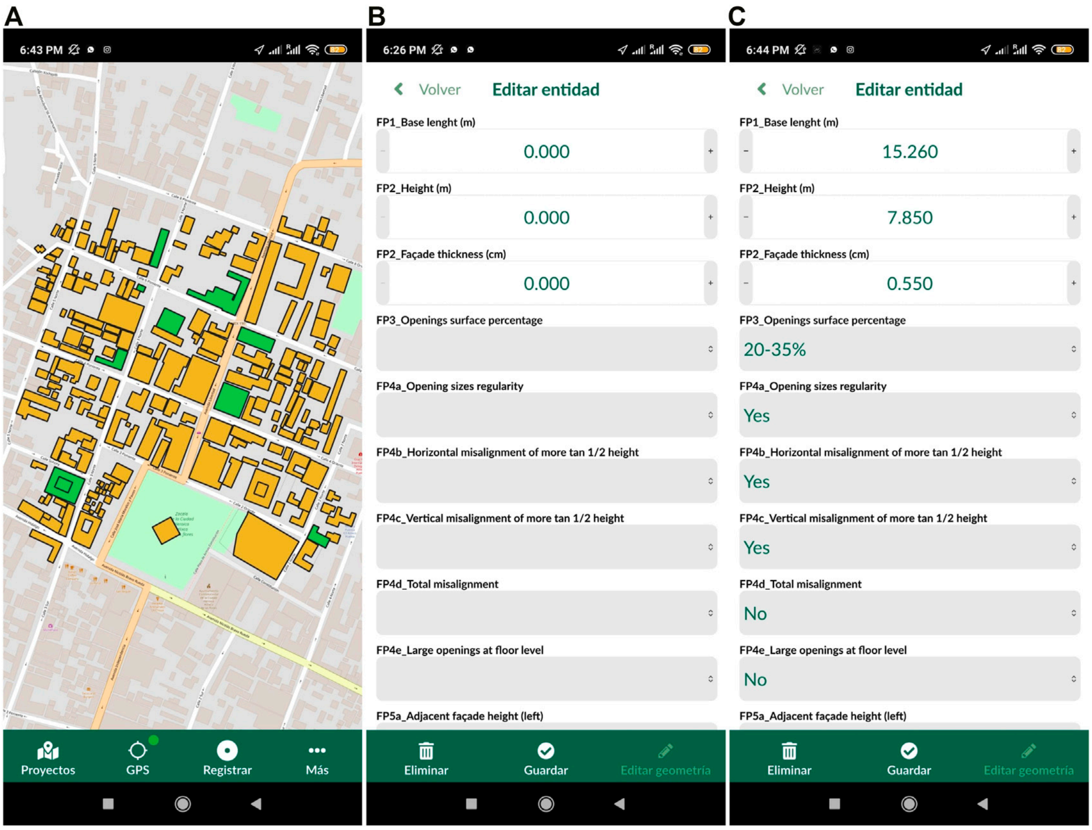


FIGURE 2 | Screenshots of the user interface of the Input app. The user interface facilitates using the device's GPS localisation **(A)** to associate geographical data to an attribute table where quantitative and qualitative vulnerability-related parameters are programmed **(B,C)**. Adapted from Eudave and Miguel Ferreira (2021).

representative semantic models (Ramírez Eudave and Ferreira, 2021a). Thought to evaluate each construction characteristic relevant for the analysis, several datasheets (such as the one of Blyth et al. (2020) for the city of Leiria, Portugal) were constructed in the form of checklists organised into different categories: building identity and use of the building, general information, openings, layout, elements connected to the façades and also connections and damages Anglade et al. (2020).

On-site inspections have a series of intrinsic advantages, such as data acquisition from a primary source and better conditions for supporting expert judgements. However, these field campaigns are often limited because they require a relatively high investment in terms of time and human resources. Hence, it is convenient to explore strategies for optimising them without losing the quality of on-site observations.

Given the proliferation and accessibility of mobile communication devices (such as tablets and smartphones), it makes sense to explore the potential of their use in site inspection campaigns. These possibilities depart from a relatively simple digitalisation of the datasheets for being fulfilled on-site (using text editors, for example) to the implementation of databases for being feed in real-time. The suitability and complexity of these strategies depend, of course, on a series of determinant conditions, such as the survey's purpose, the sample's dimension and the amount of data. A promising aspect of integrating field data acquisition and databases lies in the possibility of involving the so-called Geographic Information Systems (GIS). GIS platforms facilitate the use of several layers of information and relate them to a given spatial context. Since mapping plays a crucial role in presenting vulnerability and risk results, reducing the gap between data acquisition and geographic databases is a very attractive strategy.

Nowadays, there is a wide set of open-source and freeware tools that permit to support entire workflows integrating GIS environments, online data storage (cloud storage) and file distribution in multiple devices. An example of integration was performed for assessing the seismic vulnerability of a series of constructions in Atlixco (Mexico) (Eudave and Miguel Ferreira, 2021). This experience departs from the setup of a GIS database by using an open-source platform, that of QGIS. This software facilitates the addition of geo-referenced layers of information containing several types of data. Then, the database file is stored in a cloud service, Mergin, which offers integrated free storage for QGIS through a dedicated plug-in. Finally, the files stored in Mergin are accessible from mobile devices (based on iOS and Android OS) through a free smartphone app, Input. This app permits to consult and edit the layers of the primary QGIS file, adding data to the attribute tables. These changes in the attribute tables can be synchronised with the file stored in the Mergin service, and, consequently, these changes are immediately visible in the original database. This integration facilitates data treatment and offers an intuitive approach for data-acquisition campaigns (**Figure 2**), providing thus a more user-friendly environment for users that may be not used to specialised acquisition tools.

However, on-site data acquisition can often be replaced and/or complemented with remote-sensing and digital-based data collection methods, mainly when the external observation of the building provides enough information to perform the assessment. As a matter of fact, remote-sensing tools associated with GIS platforms have been increasingly used to get accurate three-dimensional models of the city, opening a broad set of opportunities for integrated and comprehensive urban models utilisable for multiple ends. This situation has aimed the design of common frameworks for sharing information between several digital models for the city and its components, establishing bridges among several platforms and environments.

In this regard, it is worth mentioning the CityGML standard and the Level-of-Detail framework. CityGML is a model of information intended to have a common set of classes and relationships for coding the components of the city (Kutzner et al., 2020). The result is a framework where the city is described as a network of elements defined by geometrical, topological, semantic and visual parameters, and where spatial information is managed and organised more efficiently, facilitating interaction with other standards and urban analysis. The CityGML standard also considers the capacity for representing different levels of granulometry of information according to the Level-of-Detail (LoD), which, through a series of well-defined criteria, establishes thresholds for the generalisations accepted for a model. A more detailed model intrinsically demands more resources during its creation and management. LoD permits a broad spectrum of scales, from low-detailed regional models (LoD 0) to highly detailed building models where building and fittings are modelled with a high level of accuracy (LoD 5). This versatility enables the potential interaction with other types of models at the scale of the building, such as the Building Information Models (BIM). Applicable both to new and existing buildings, BIM can be understood as a set of processes and methodologies that permit managing all the aspects of a building over its entire lifespan. BIM is based on the organisation of components and their relations, allowing to work at different levels, according to the level of detail and the number of processes included in the model. Thanks to the Industry Foundation Classes (IFC) standard, it is feasible to have a shared repository of elements and systems (Donkers et al., 2016). This integration has reached capabilities such as the automatic and semi-automatic conversion of elements among standards, as shown by Donkers et al. (2016).

In Ramírez Eudave and Ferreira (2020), the authors suggest a possible integration of data acquisition strategies, three-dimensional urban models, and BIM files, organised in a general GIS framework. This workflow would facilitate the integration of urban-scale risk assessment strategies that can be further developed and detailed if needed, generating risk-oriented databases inside accumulative and comprehensive GIS models. **Figure 3** schematises how the first step for describing the urban environment is the selection of descriptors (i.e., the attributes that are considered as representative). These descriptors must be coded as qualitative, quantitative or semi-quantitative data in correspondence to the physical reality. For example, the height of a building can be a descriptor for a group of constructions. When the height of a specific construction is measured, coded and registered, that descriptor becomes a part of the description of the building. This association can be performed by on-site observations, remote surveys or even documental sources. The set of descriptions is, therefore, a model of the physical entity and can be stored in multiple formats and supports. Among other ends, the model can be used to perform vulnerability assessments if there is coherence and correspondence between the vulnerability assessment approach and the information contained in the model.

3.2 Assessing Earthquake, Fire and Flood Risk in Historic Urban Areas

Because of the scale and the amount of data involved, simplified methodologies, often based on sets of empirically-defined evaluation parameters, are usually more adequate to perform large-scale assessments. However, the suitability of using simplified models of the city and its elements depends on multiple factors, such as the limits imposed for processing the information, the heterogeneity among the constructions (e.g., uses, constructive systems, the urban layout, etc.) and the data acquisition capacities. It is convenient to observe that these and some other conditions may constrain the advantages offered by simplified approaches; a successful assessment should be aware of the method's reliability in the context of its limitations and assumptions.

3.2.1 Earthquake

According to United Nations, earthquakes are the natural hazard with the highest ratio between the amount of material and human losses and the number of events disasters (United Nations Office for Disaster Risk Reduction, 2018). Hence, a good understanding of the seismic vulnerability level of the building stock is critical, particularly in active seismic regions. Assessing the seismic vulnerability of large building stocks is still a demanding task, not only due to the complexity inherent to the assessment itself but also to the difficulty in managing all the data required to characterise the structures accurately. Historic Urban Areas are particularly challenging contexts with different building typologies (often divergent) coexisting in the same space, which significantly limits the resource to any general assumption or generalisation. Nevertheless, the definition of building typologies is not only possible but highly useful in the context of risk assessment, as discussed by Santos et al. (2013) and Salazar and Ferreira (2020). In what regards to masonry buildings, which is the most recurring structural system in Historic Urban areas (Roca et al., 2010), the adoption of masonry-oriented simplified strategies for approaching the historic city has become common.

Gavarini (2001) offers a definition of vulnerability devoted to the structural performance of constructions in historical centres:

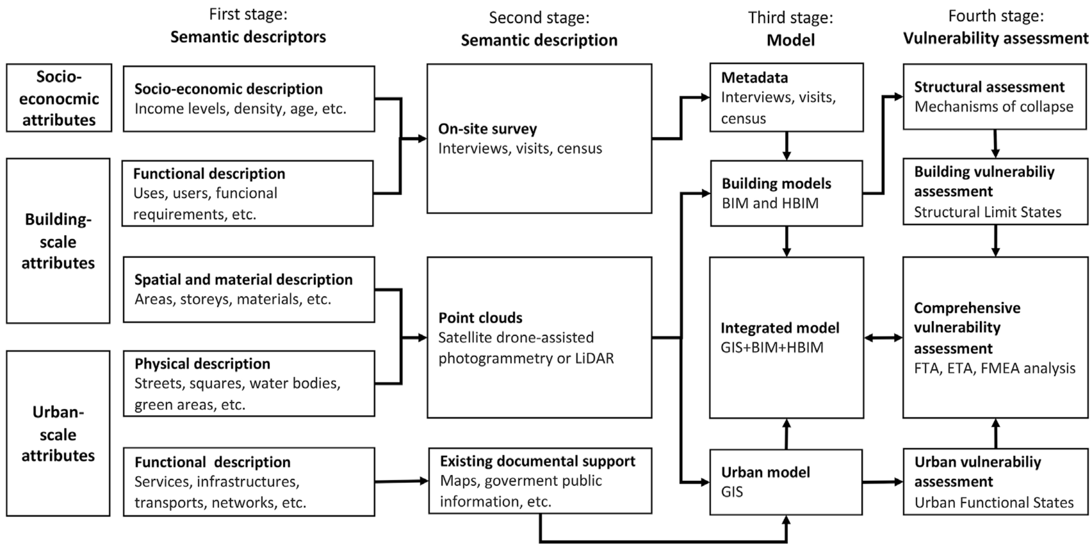


FIGURE 3 | Potential multi-scale integration for data-acquisition. Four main stages are considered in this framework for characterising the urban environment: Selection of descriptors, surveying processes, modelling and assessment. The model also contemplates a multi-scale classification for each step. Adapted from Ramírez Eudave and Ferreira (2020).

TABLE 1 | Vulnerability Index parameters, vulnerability classes, C_{vi}, and weights, p_i, calibrated by Ferreira et al., 2017b.

Parameters		**Class, C_{vi}**				**Weight**	**Relative weight**
		A	**B**	**C**	**D**	**p_i**	
Group 1. Structural building system							
P1	Type of the resisting system	0	5	20	50	2.50	50/100
P2	Quality of the resisting system	0	5	20	50	2.50	
P3	Conventional strength	0	5	20	50	1.00	
P4	Maximum distance between the walls	0	5	20	50	0.50	
P5	Number of floors	0	5	20	50	0.50	
P6	Location and soil condition	0	5	20	50	0.50	
Group 2. Irregularities and interaction							
P7	Aggregate position and interaction	0	5	20	50	1.50	20/100
P8	Plan configuration	0	5	20	50	0.50	
P9	Height regularity	0	5	20	50	0.50	
P10	Wall façade openings and alignmen	0	5	20	50	0.50	
Group 3. Floor slabs and roofing system							
P11	Horizontal diaphragms	0	5	20	50	0.75	18/100
P12	Roofing system	0	5	20	50	2.00	
Group 4. Conservation status and non-structural elementsl							
P13	Fragilities and conservation status	0	5	20	50	1.00	12/100
P14	Non-structural elements	0	5	20	50	0.75	

"the seismic vulnerability of a building is a quantity associated with its 'weakness' in front of earthquakes of a given intensity so that the value of this quantity and the knowledge of seismic hazard allow to evaluate the expected damages from future earthquakes". Vicente et al. (2005) highlight this causal relation when he defines seismic vulnerability as "an intrinsic property of the building structure, a characteristic of its own behaviour to seismic action described by a cause-effect relationship, in which the earthquake is the cause, and the effect is the damage suffered".

The *Gruppo Nazionale per la Difesa dai Terremoti* (GNDT-SSN, 1994) is the author of one of the most recognised proposals

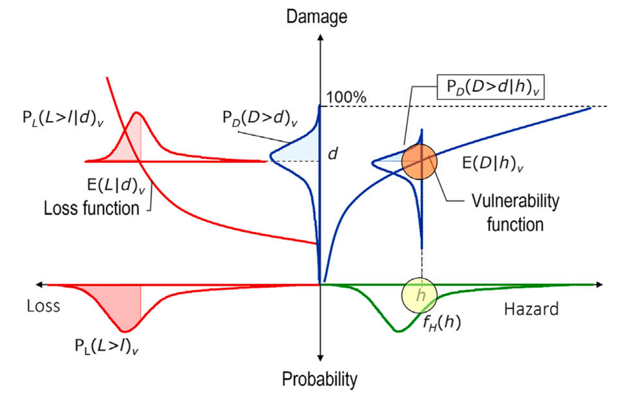


FIGURE 4 | Conceptual framework of the vulnerability-based approaches. Adapted from Vicente (2008).

for assessing the seismic vulnerability of large samples of buildings. From the detailed analysis of large sets of post-earthquake data gathered in the sequence of several seismic events in Italy, GNDT's proposal grounds on implicit and explicit correlations found between the damages suffered by the buildings and their material, construction and geometrical properties, operationalised through a series of evaluation parameters which allow estimating the seismic vulnerability of the building, see **Table 1**. According to this formulation, each parameter is evaluated based on four increasing vulnerability classes (A, B, C and D) and weighted through a series of weights, p_i whose value illustrates the relative importance of that parameter (building feature) to the overall seismic vulnerability of the building. Although the application of this method is limited to the building typologies for which those correlations were obtained, it has been successfully adapted and applied in countless vulnerability assessment works in many countries and contexts, including Coimbra (Vicente et al., 2011), Seixal (Ferreira et al., 2013), Horta (Ferreira et al., 2017b) and Leiria (Blyth et al., 2020), in Portugal; Annaba, in Algeria Athmani et al. (2015); Timisoara, in Romania (Mosoarca et al., 2019); Osijeck, in Croatia (Hadzima-Nyarko et al., 2016), and Atlixco, in Mexico (Ramírez Eudave and Ferreira, 2021b); which proves the versatility the approach.

As presented in **Figure 4**, the vulnerability, expressed here in the form of a vulnerability curve, makes the bridge between the hazard and the probability of reaching discrete levels of damage for different seismic intensity levels. According to the schematisation illustrated in the figure, for such, a probability density function associated with a discrete seismic hazard value should be first defined. Then, for a given hazard value, and knowing the vulnerability of a building typology, V, a mean damage grade and a dispersion value can be obtained from the vulnerability function, $E(D|h)_v$, and the fragility curves, respectively. Finally, to assess the absolute risk, i.e., to estimate the value of losses, it is necessary to convert damages into losses using damage factors. As an example, to estimate economic losses, a repair cost is associated with each damage state, using a damage factor (dimensionless quantity) defined as the quotient between the repair cost and the replacement cost. Thus, the damage indicators are converted into losses using a loss function, $E(L|d)_v$, and finally, the probability distribution of losses is obtained and described by its probability density function, $P_L(L>l)_v$ (Vicente, 2008). This vulnerability-based approach makes it relatively easy to estimate the seismic vulnerability of large building stocks, see **Figure 5**. Given that the expected level of damage is based on the vulnerability of the building and on a deterministic hazard indicator, it is then possible to create scenarios associated with different return periods.

The possibility of using this approach to identify characteristic vulnerabilities and to get a feeling of the possible impact resulting from the application of specific seismic retrofitting techniques is another remarkable feature of these index-based approaches, and which makes them very interesting decision-making supporting tools. An example of this can be found in (Ferreira et al., 2017a). In that work, the authors use a simplified index-based approach to evaluate the impact of adopting different large-scale retrofitting strategies, measured in terms of material, human and economic losses. A GIS tool wherein georeferenced graphical information was combined and connected to a relational database containing the main structural characteristics of the buildings was used by the authors to improve results visualisation and interpretation. According to the authors, the work aimed not only to demonstrate how simplified seismic vulnerability assessment approaches can be used to analyse the impacts resulting from the implementation of large-scale retrofitting programs but also to prove that investing in prevention strategies designed to mitigate urban vulnerability is one of the most effective strategies, both from the human and economic standpoint.

The advantage of having a probabilistic-based approach for earthquake-related losses and collapses is that it also facilitates a framework for establishing risk acceptability thresholds based on a series of metrics. It is possible, for example, to estimate the number of buildings that are expected to be unusable after a determined event making it possible, as a result, to estimate the number of homeless people. Or, in the same line, to estimative the number of building collapses and, based on that, the potential number of human casualties. Last but not least, damage indices can be used to estimate replacement costs and, based on that, to assess the economic viability of different seismic rehabilitation interventions and identify the buildings that, due to the extension of the damages, are economically viable to be repaired. If associated with the probability of exceeding certain intensity levels, this procedure allows establishing thresholds for acceptable risk.

Another relevant application of index-based approaches is to analyse the potential accumulation of debris resulting from the partial or global collapse of buildings, which can compromise pedestrian safety in post-earthquake scenarios, see **Figure 6**. Based on such results, decision-makers can base their decisions on the knowledge of the urban areas that can be potentially inaccessible, which routes can constitute alternatives for evacuation purposes, and where debris removal actions should be concentrated (Bernardini and Ferreira, 2022). Furthermore, urban evacuation scenarios are privileged tools to

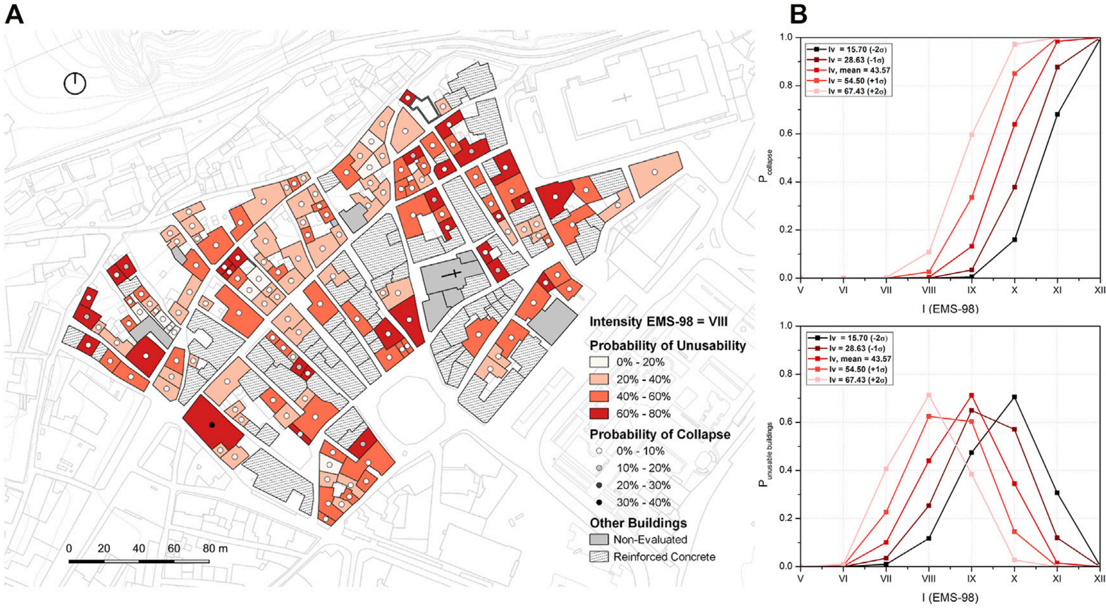


FIGURE 5 | Mapping of the probability of collapses for an intensity VIII in the 1998 European Macroseismic Scale (EMS-98) **(A)**, and collapse and building unusable probability curves obtained from the mean value of the vulnerability distribution **(B)**. For details on how these outputs were obtained please refer to Blyth et al. (2020).

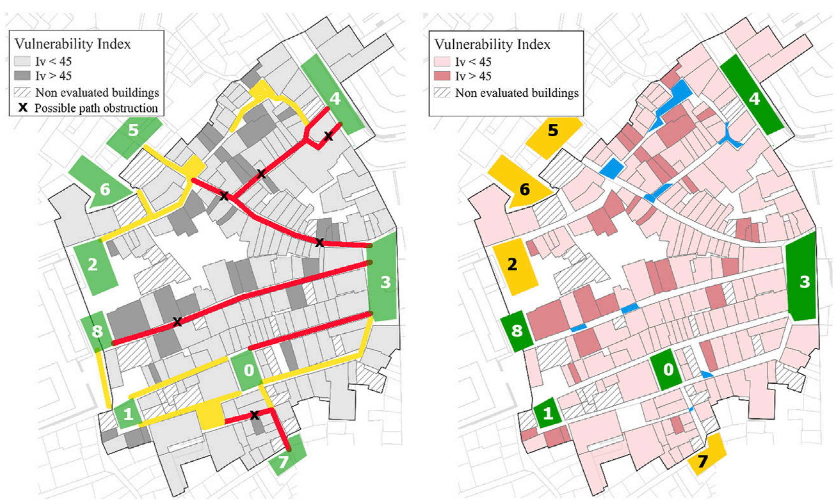


FIGURE 6 | Identification of gathering areas (in green and yellow, including identification code 0–8) and of the streets with >50% (red) and <50% (yellow) of the area occupied by debris. Streets blockage positions induced by debris are also identified with an "X", and "spontaneous" gathering areas are identified in blue (Bernardini and Ferreira, 2021). Maps like these facilitate the identification of critical failures on urban functions in post-event scenarios, providing valuable information for emergency planning and response decisions.

promote awareness-raising actions among the general population.

3.2.2 Fire

The characterisation of fire risk in urban areas is a very challenging task due to the many technical attributes involved, including numerous non-linear and multidimensional interactions. This is even more true in the case of existing buildings, not only because the number and the magnitude of the uncertainties involved in the process are more significant but also because most of the existing fire-oriented risk assessment methodologies are devoted to new structures. There are, however, a number of methods that, originally developed to existing structures or not, can be applied for that end (Julià and Ferreira, 2021). A very suitable method in the context of historic city centres is the ARICA method—an acronym for

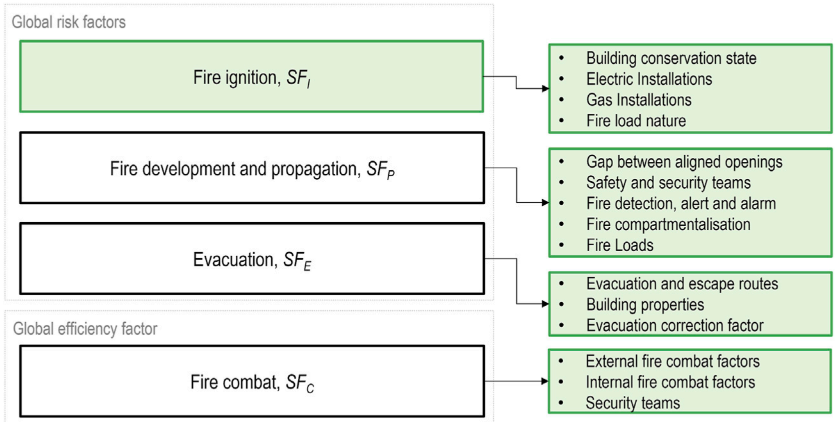


FIGURE 7 | Global Risk Factors and Global Efficiency Factors and their corresponding partial factors. Adapted from (Granda and Ferreira, 2019).

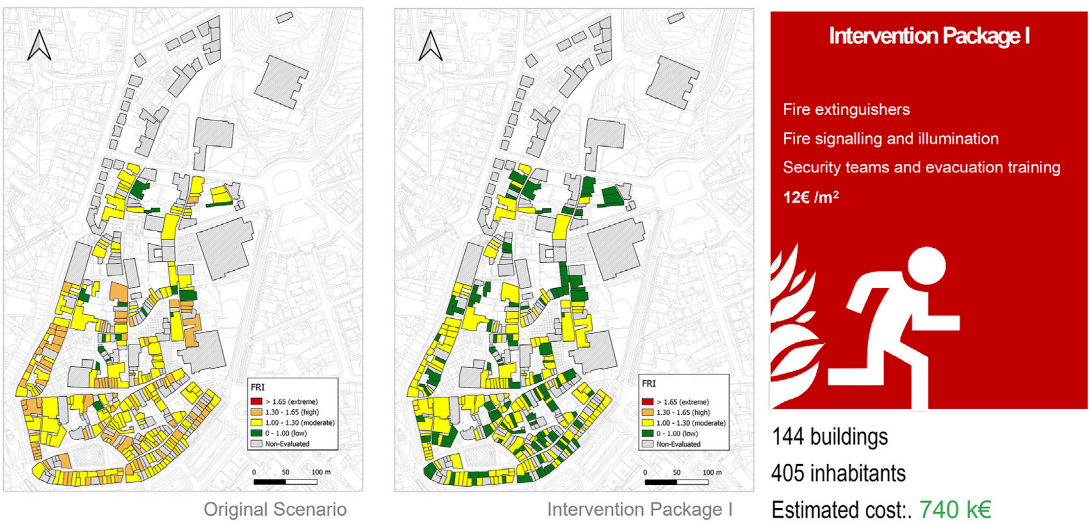


FIGURE 8 | Cost-benefit analysis of implementing an intervention package for the city of Guimarães. Adapted from Tozo Neto and Ferreira (2020).

"Fire-risk Assessment in Ancient City Centres" ("*Avaliação do Risco de Incêndio em Centros Urbanos Antigos*", in Portuguese). Based on the Portuguese fire safety code (Granda and Ferreira, 2019), this method is based on the evaluation of four global fire risk factors: Three global risk factors and an efficiency factor (FGE), covering all the fire cycle from ignition and development to evacuation and combat, see **Figure 7**.

In this semi-quantitative method, each of the parameters listed in **Figure 7**—all associated to a quantitative value that reflects the degree of adequacy of the building in relation to a series of features prescribed in the Portuguese Fire Safety code—is evaluated individually. For the sake of example, the partial factor "Fire detection, alert and alarm" can take a value between 0.50 and 2.00, where 0.50 represents the best-case scenario of a building with an operational automatic fire detection system, and 2.00 corresponds to the worst-case scenario of a building with no fire detection, alert and alarm system in place. Then, by dividing the weighted average of the four sub-factors mentioned above by a reference risk factor related to the building's use, it is possible to get a fire risk indicator, FRI, which is directly relatable to the level of fire safety equivalent to that corresponding to full compliance with the Portuguese Fire Safety code. Despite the simplifications involved, the results obtained with this approach are valuable for providing fire risk maps similar to the ones shown in **Figure 8** (left), which present the results of the application of the ARICA method to the 436 buildings that compose the Historic City Centre of Guimarães (Granda and Ferreira, 2019).

Similarly to what was discussed earlier for the index-based seismic vulnerability assessment approaches, the ARICA method can also be used to identify the areas of the city where there is a higher concentration of vulnerable buildings, as well as to

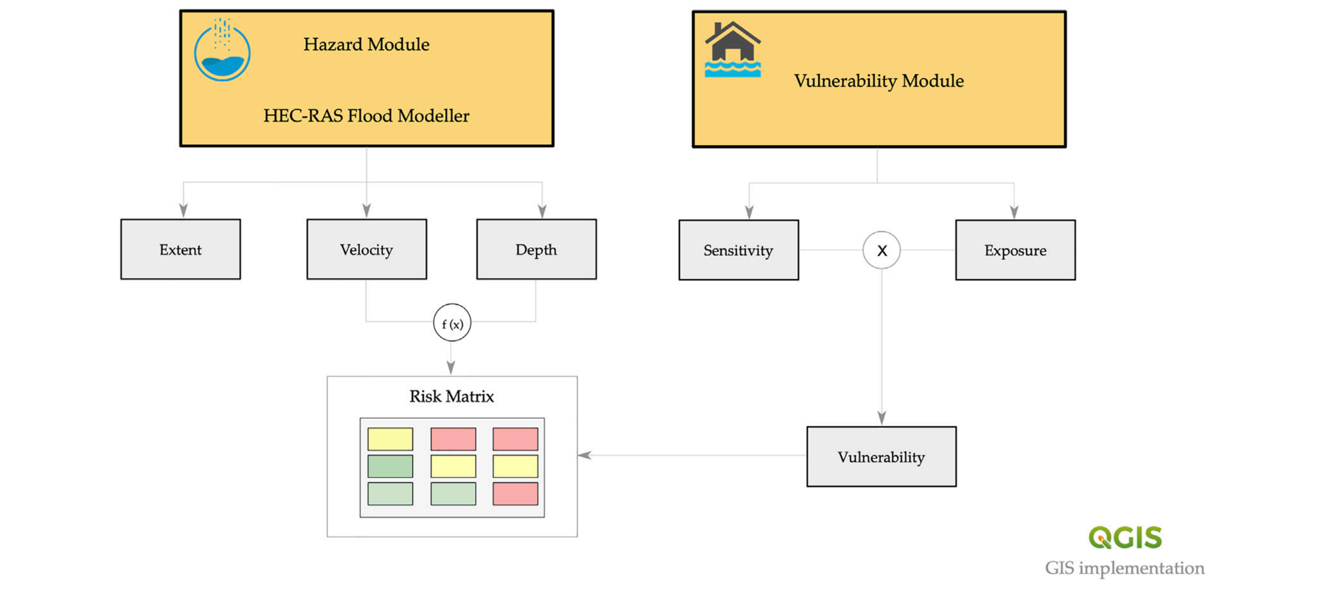


FIGURE 9 | Conceptual framework of the flood risk assessment approach proposed by Ferreira and Santos (2020). The final risk matrix is obtained from the combination of hazard and vulnerability results.

quantify the potential human and economic benefit resulting from the application of different retrofitting strategies (Tozo Neto and Ferreira, 2020), see **Figure 8**. Also in this case, the cost-benefit analysis is conducted by emulating a series of actions specifically tailored to address the vulnerabilities identified in the partial factor assessment. In this specific case of the example illustrated in **Figure 8**, Intervention Package I (IP-I) included fire risk mitigation interventions possible to be applied in a straightforward and not expensive way, without the need for any modification in the existing structure. It is composed of essential fire safety items, such as fire extinguishers and signalling, including also measures related to risk perception and training. From this analysis, the authors concluded that the adoption of the set of measures included in this IP-I would lead to a significant reduction of the level of fire risk identified in the Original Scenario (**Figure 8**, left). According to the authors, and as can be observed in **Figure 8**, the number of buildings identified with low-risk increased from 16 (about 6% of the total) to 108 (about 40% of the total). Moreover, the buildings that in the Original Scenario were categorised with high risk saw their level of risk reduced to moderate with the application of these measures.

As can be easily understood from this example, this process allows simulating a set of generic actions that would be suitable for mitigating a number of vulnerability-related aspects under the basis of parametric costs (e.g., based on units of area) that can be easily calculated. And this can be repeated and reimplemented as many times as necessary until an acceptable level of risk is reached, constituting thus a flexible and relatively simple approach for defining risk management policies.

3.2.3 Flood

Though flooding can be associated with several sources, it is often related to heavy rainfalls and the lack of capacity of natural watercourses for conveying the water flow (Julià and Ferreira, 2021). There are two fundamental types of approaches to assess flood risk: those focused on analysing the hazard and those focused on the vulnerability assessment of the element at risk. The hazard-oriented approaches are primarily based on parameters as the extent, velocity and depth of the flows, whereas the vulnerability-oriented approaches are based on the characterisation of the elements exposed to the flood (e.g., buildings and/or infrastructures) for obtaining a flood vulnerability indicator that mirrors the propensity of these elements to withstand with the flood with more or less damage. Although these two approaches are very different in scope and purpose, they can both be used to get valuable risk-related outputs, either when used independently or together, as per the example shown in **Figure 9** where a flood hazard and a flood vulnerability indicator are put together to get a flood risk matrix. The components of the hazard module are the maximum extent of the flood (for a 100-year peak flow scenario), the average surface velocity of the flow (in m/s) and the maximum depth (the distance between the floor and the surface of water) associated with the maximum extent. The vulnerability module assesses the sensibility of the construction (based on its heritage status, age, number of storeys, condition and material of the building) and the level of exposure (partial or total; with or without openings) of a wall towards the water flow. The detailed criteria for grading each parameter can be found in (Ferreira and Santos, 2020).

In the approach schematised in **Figure 9**, the flood hazard was assessed using the hydraulic method. The assessment process involved acquiring and preparing geometric data, estimating the peak flow, hydraulic modelling, and GIS post-processing and mapping. Regarding flood vulnerability, it was assessed using the simplified flood vulnerability assessment methodology proposed by (Miranda and Ferreira, 2019). This methodology is based on the evaluation of two vulnerability components, an exposure and a

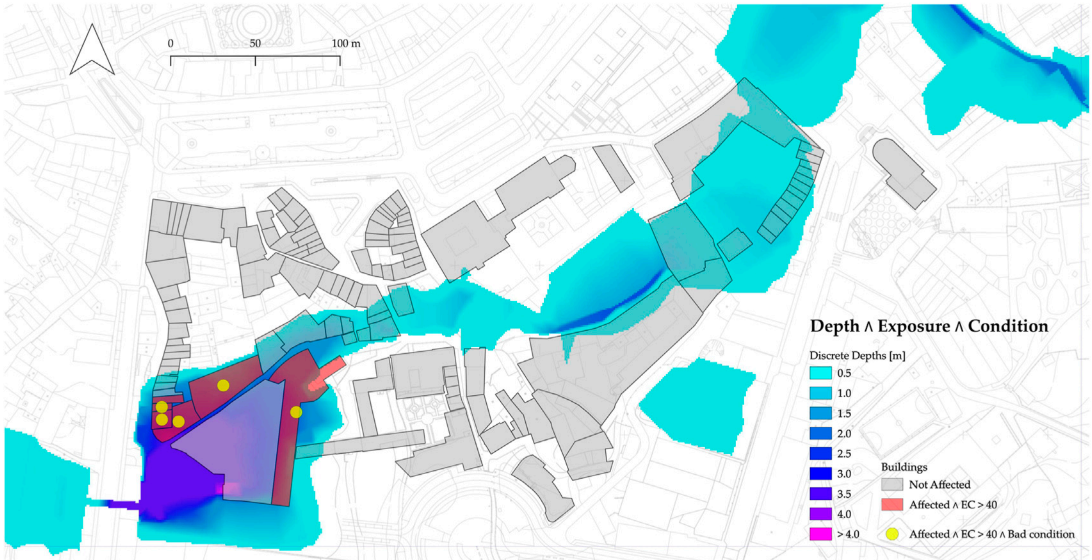
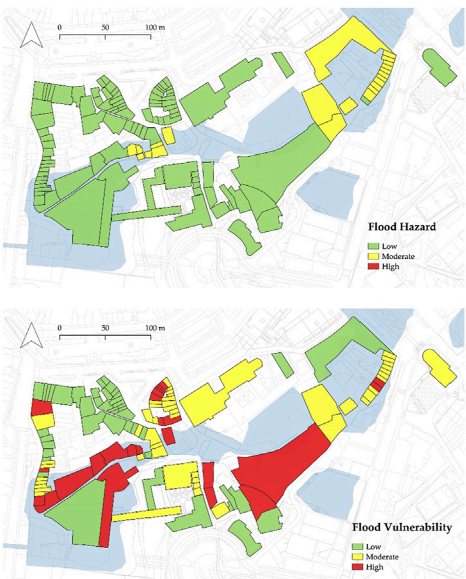


FIGURE 10 | Example of a joint analysis of water depth, exposure, and condition (i.e., buildings' conservation state) indicators (Ferreira and Santos, 2020). This kind of output makes it easy to analyse flood risk scenarios from the combination of hazard and physical vulnerability-related results.



Flood Risk		Hazard		
		Low	Moderate	High
Vulnerability	High	19 (16.4%) Middle Risk	5 (4.3%) High Risk	0 High Risk
	Moderate	33 (28.5%) Low Risk	15 (12.9%) Middle Risk	0 High Risk
	Low	42 (36.2%) Low Risk	2 (1.7%) Low Risk	0 Middle Risk

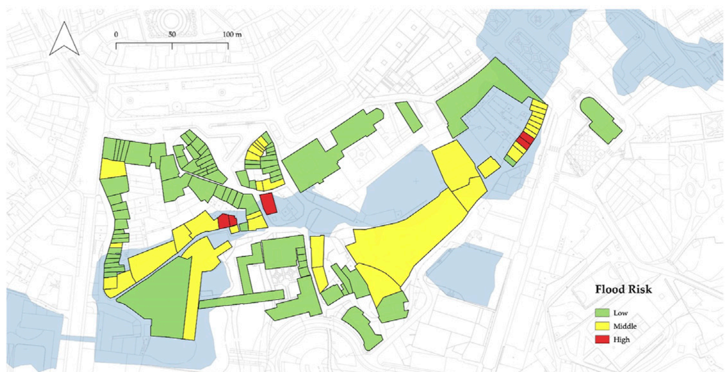


FIGURE 11 | Example of a flood risk matrix based on the combination of the level of Hazard and Vulnerability obtained for each building. The numbers and the percentages included in the tables represent the number and percentage of buildings categorised with that specific level of risk.

sensitivity component, which, through an index, quantify the vulnerability of the building to flood inundation. Whereas the exposure component is given by one single parameter/feature, the orientation of the front wall of the building, the sensitivity component brings together a series of parameters related to the physical characteristics of the buildings, namely its type of structural system, conservation state, number of storeys, age, and heritage status.

Moreover, one of the significant advantages of this type of index-based approaches in general, and this one in particular, is the possibility of crossing and analysing together not only the final hazard and vulnerability indicators but the intermediate hazard outputs and building features that led to those indicators, as explored and discussed by (Ferreira and Santos, 2020). An illustrative example of this is the joint analysis of the water depth estimation for a specific peak flow scenario and the exposure and conservation state of the buildings, shown in **Figure 10**. Such an output allows getting a feeling of the buildings that are likely to be affected for that specific scenario and, most importantly, those likely to be more affected due to their higher level of exposure and poorer conservation state. The assessment of these features is, of course, intimately related to the three-dimensional configuration of the city, thus favouring the use of GIS environments.

Despite the empirical nature of the methodology, it can be extremely valuable to support decision-making processes by making it easy to compare and identify the assets at higher risk, as explained before. Final risk matrices play an essential part in this decision-making process by providing an additional layer of information related to the level of risk decision-makers and stakeholders are willing to accept, see **Figure 11**. The number and thresholds for the levels of risk can be decided according to a broad series of criteria, facilitating the use of this tool for establishing bridges among stakeholders. Last but not least, this type of approach can also be used in a simple but effective way to analyse how different flood risk mitigation interventions, at the building or the urban scale, can impact the level of risk associated with each construction. Furthermore, this approach can support emergency planning and response actions, namely those related to evacuations and immediate actions; for example, (Quagliarini et al., 2022).

4 BUILDING KNOWLEDGE AS A PART OF RESILIENCE ENHANCING PROCESSES: THE USE OF ARTIFICIAL INTELLIGENCE APPROACHES

The methodologies reviewed succinctly in the above sections have resulted from a thorough analysis of several seismic, fire and flood events and various applications to case study areas in various contexts and geographies. Although this is done today using stabilised scientific processes and taking advantage of state-of-the-art numerical tools, the idea of learning from past destructive events and applying that knowledge in construction practice is far from new. As a matter of fact, this was common practice before the advent of modern science and, therefore, it is mirrored in a very clear way in intervention, uses, configurations and technologies used for centuries in our city. Just as an example, the destruction of the city of Lisbon after the 1755 Earthquake led to the development of a new type of seismic-resistant structural system known as “gaiola Pombalina” or Pombaline cage, in a direct translation to the English (Ferreira et al., 2017a). The diversity of structural systems and adaptative strategies is the living example of resilience towards adverse situations and conditions (Baquedano et al., 2021). Hence, building significant learning from the basis of past events is not only a proactive task but a reactive part of long-term resilience and adaptation processes.

As seen in the previous sections, large-scale vulnerability assessment methods are often based on a few empirical-based parameters defined through the statistical analysis of large sets of post-event damage data, usually resorting to very simple mathematic expressions. However, the inability of these traditional methods to handle missing or noisy data or to identify certain behaviour patterns opens up space to the use of innovative computer-based solutions. In the last couple of years, artificial intelligence-based approaches are becoming increasingly popular in many civil engineering applications (Ferreira et al., 2020). Such approaches, which include Machine Learning, Heuristics, Metaheuristics or Bayesian networks, just to mention some, are extremely valuable for understanding complex events, classifying data and optimising resources. These tools are especially useful for supporting processes in which it is difficult to guess the origin of a determinate outcome that may result from different processes. To give an example outside the scope of this paper’s topic, this is the case of the identification between viral and bacterial meningitis, in which artificial intelligence may play a relevant role when advanced clinical tools are not available (D’Angelo et al., 2019).

The assessment of the effects of different types of hazards is one of the many fields in which these approaches may be potentially valuable. In fact, it is possible to identify many works in the literature that can be easily relatable to common issues identified in urban risk analyses. Pasha et al. (2020), for example, have studied how to optimise a route based on several parameters. Although this study is applied to supply chain-related problems, the rationale behind the strategy outlined by the authors also applies to disaster scenarios where supply networks and vehicle logistics are conditioned for numerous aspects determined by the loss or significant reduction of urban functions. In the same line, efficiency-related decisions during emergency evacuations have been explored by Dulebenets et al. (2019). This model proposes the characterisation of vulnerable population groups, emergency shelters, evacuation routes, traffic conditions, etc., in order to minimise individuals’ travel time and to prioritise groups for which specific vulnerability indicators have been found.

Following this very same rationale, the use of robust statistic approaches and the selective systematisation of data has permitted a better understanding of the nature of risk, particularly nowadays with the exponential growth of machine learning, data mining and artificial intelligence applications. In fact, even if the significance of empirical knowledge is undeniable, the wide range of increasingly powerful and cheaper computational resources available today open possibilities that were not only unreachable but unimaginable just a few decades ago.

In the specific case of vulnerability and risk assessment methodologies, when compared with traditional statistical methods, innovative computed-based approaches present the great advantage of being able to handle missing or noisy data and managing nonlinearities and identifying specific behaviour patterns hardly identifiable through traditional approaches (Ferreira et al., 2020). This is not only valid for developing new methodologies or assessment approaches but also for calibrating existent ones, as discussed by (Ferreira et al., 2020) where the authors compared the performance of a traditional vulnerability index methodology and an

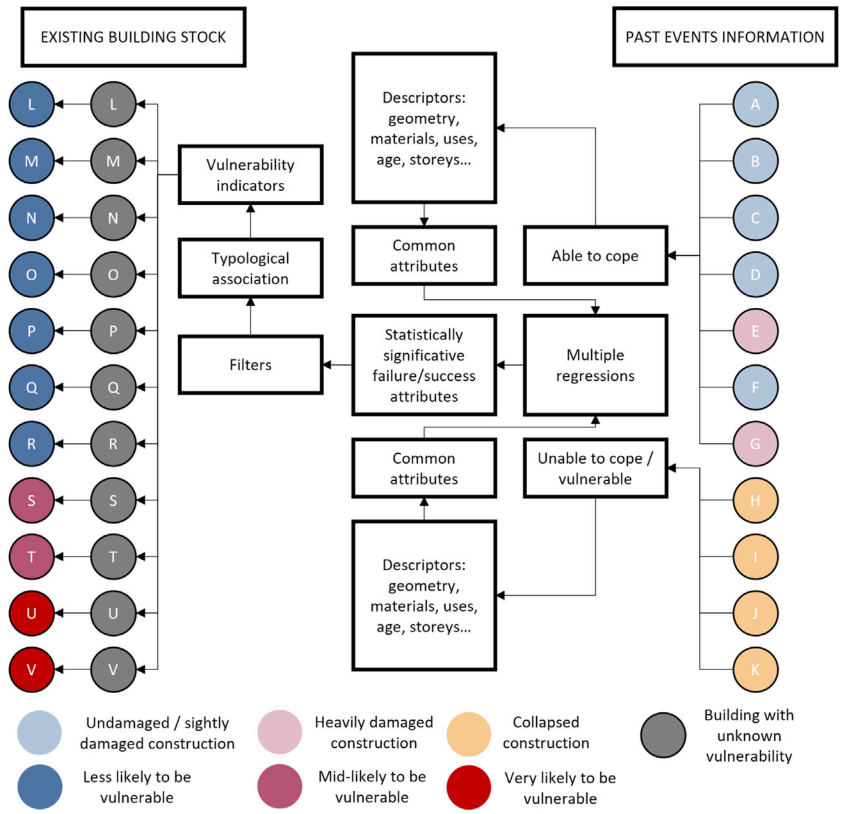


FIGURE 12 | Example of workflow for analysing past-events data for assessing existing buildings. Buildings on the right side (letters A to K) were assessed after a determined seismic event, feeding a series of processes (in the middle) to find the typology's vulnerability sources. Buildings with an unknown level of vulnerability (letters L to V) are compared with these vulnerability sources to identify the structures that are potentially more prone to damage in the sequence of a future seismic event.

innovative approach based on Artificial Neural Networks (ANNs) though comparing their results with real post-earthquake damage observation. As schematised in **Figure 12**, the characterisation of past hazardous events and the finding of the attributes that may have conditioned the ability of the buildings to cope with them can be a valuable asset towards finding reliable and accurate vulnerability indicators. Each one of the letters in **Figure 12** represents a building representative of a specific typology, such as, for example, a traditional masonry building with granite stone walls and wooden floors. The buildings labelled with the letters A to K has been subjected to a seismic event. From those, A to G revealed an adequate seismic performance (with different levels of damage), whereas H to K collapsed. The characteristics of all these buildings were then assessed to find statistically significant features shared between the buildings included in the first and in the second group. Through this process, it is possible to isolate and understand the factors that influence the most the seismic performance of that specific building typology. Finally, the assessment of those characteristics on buildings with an unknown level of seismic vulnerability (L to V) would allow estimating the level of damage that those buildings would likely suffer if subjected to a seismic event similar to the one(s) used in the analysis.

Furthermore, exciting advances in the use of Multiobjective Evolutionary Algorithms (MOEAs), a framework for conducting comparatives in which the sensitivity of inputs and robustness of models can be tested, has been recently observed. The work of Zhi-Zhong et al. (Liu et al., 2020) illustrates how such a framework can be used to overcome some of the limitations of Many-Objective Problems (MaOP). The quality of the solutions depends on the obtention of the problem features—a task that can, itself, be done using learning automatons (Zhao and Zhang, 2020).

5 FINAL REMARKS

Built cultural heritage is at increasing risk due to climate change and anthropic actions. The frequency and severity of extreme events are rising, imposing new challenges on traditional risk management practices in urban areas. Since disasters will continue to occur, it is necessary to anticipate those challenges by forecasting potential scenarios in the most accurate and reliable way possible—and risk assessment is the key for that. Nowadays, digital tools facilitate many tasks related to risk identification, assessment and management, such as geometric survey, damage mapping, monitoring, vulnerability assessment, management and more. Despite the level of uncertainty associated with vulnerability assessment methodologies based on statistical approaches and damage observation, they offer a very interesting compromise between the amount of input data and computational effort required to perform the analysis and the reliability of the results produced, which make them very suitable tools for assessing large urban areas. Furthermore, the use of geographical databases and the assistance of remote-sensing tools are opening a vast horizon on interoperability and comprehensiveness for urban-scale models. As discussed in the present article:

- Simplified vulnerability and risk assessment approaches can play a significant role in providing preliminary scenarios and pointing the way to the definition of more efficient and customised strategies for managing and mitigating risk. The knowledge built on the consequences of past events permits refining and calibrating our present-day vulnerability and risk models, allowing us to understand better the phenomena involved in these processes. This is relevant not only for the decision-making process, allowing for more accurate and effective decisions, but also because it promotes better engagement of stakeholders and professionals with different expertise and backgrounds, which is critical towards promoting safer and more sustainable urban areas. Despite so, it is important to acknowledge that these approaches are based on several assumptions an generalisations, which must be understood and recognised. Although they are very handy and suitable to assess large datasets, they are likely to overcome important local phenomena or conditions, which may completely change the outcome of the analysis. In this sense, the implementation of these approaches must always be preceded by a discussion about its suitability and pertinence according to the context.
- As addressed in **Section 4**, artificial intelligence-based approaches are extremely promising towards getting more accurate and reliable risk assessment models. However, it is crucial to recognise and acknowledge the need for more and better training data, under the risk of the results obtained from these models can be dangerously misleading.

The present study addresses strategies for characterising, assessing and treating risk in historic urban areas. Most of the experiences discussed herein are still to be fully established or validated, which means that their potential is not entirely exploited yet, or even understood in some cases. The potential for improvement and development in this field is, therefore, readiness, and new, more accurate, and more excited risk assessment approaches able to overcome the limitations of the current ones can be just around the corner.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualisation, TMF; investigation, TMF and RRE; writing—original draft preparation, RRE and TMF; writing—review and editing, TMF and RRE; supervision, TMF; funding, TMF. All authors have read and agreed to the published version of the manuscript.

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Multi-Hazard Chain Reaction Initiated by the 2020 Meilong Debris Flow in the Dadu River, Southwest China

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Delivery of large volumes of sediment by debris flows in a short time into rivers often initiates a hazardous chain reaction in alpine valleys. Predicting the multi-hazard chain's evolution and intervening in its cascading effects by artificial countermeasures face major challenges due to the spatial and temporal variability of controlling factors. On June 17, 2020, a rainstorm-induced debris flow event with a volume of 2.4×10^5 m^3 occurred in the Meilong catchment, Danba County, Sichuan Province, Southwest China, which triggered a debris flow–outburst flood–landslide hazard chain. Large amounts of sediment entered the Xiaojinchuan River and formed a barrier lake. The outburst flood and narrowed river flow eroded 2.76×10^6 m^3 of deposits and reactivated the Aniangzhai landslide. Engineering measures were implemented to prevent the hazard, including dredging, rechanneling, and embankment construction. The deformation rate and acceleration of the landslide decreased from a peak of 75 mm/h to 8.74 mm/h and a peak of 16.46 mm/h^2 to 0.13 mm/h^2 before and after the engineering, respectively, according to measurements of a ground-based monitoring radar. Without the engineering measures, the factor of safety of the landslide would be reduced to 0.93, and a larger landslide dam hazard would occur if the foot were eroded by more than 17 m. The case and its successful engineering demonstrate that artificial intervention measures are effective in halting the cascading process of natural hazards.

Keywords: debris flow, cascading hazards, landslide stability, barrier lake, river erosion

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INTRODUCTION

Large debris flows or avalanches that occur in narrow alpine valleys are likely to block rivers and trigger a multi-hazard chain, causing serious damage to settlements and infrastructure (Davies 1997; Korup and Clague 2009; Cui et al., 2015). The chain usually comprises landslides, dammed lakes, and outburst floods (Reneau and Dethier 1996; Cui et al., 2011; Kappes et al., 2012). In general, the total loss caused by such a multi-hazard chain is far greater than that caused by a single hazard (Chai et al., 1995; Xu et al., 2010; Chen et al., 2011; Ma and Kaiheng, 2013). Recent events, e.g., the 2007 and 2010 Tianmo debris flows (Ge et al., 2014; Deng et al., 2017) and the 2018 Sedongpu debris flows in southeastern Tibet (Hu K. et al., 2019), demonstrate that the multi-hazard chain may affect great spatial and temporal extents than a debris flow.

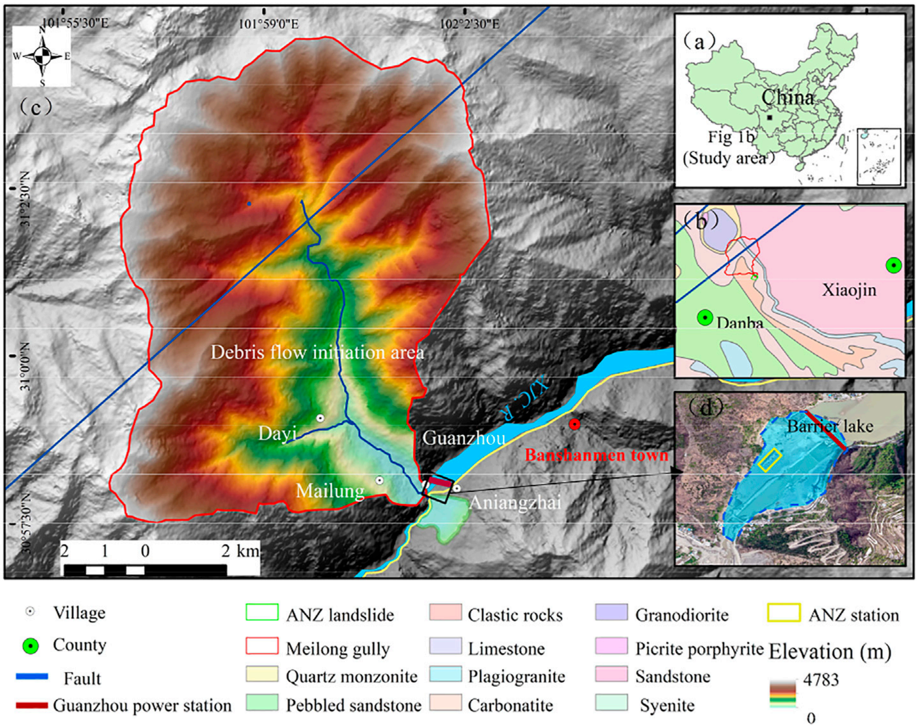

FIGURE 1 | Regional settings and locations of the Meilong valley and ancient ANZ landslide. **(A)** Location of the study area. **(B)** Lithology of the study area. **(C)** Topographic features and fault distribution. **(D)** Meilong barrier lake. XJC R is the Xiaojinchuan River. ANZ L is the Aniangzhai landslide.

Previous researches are focused on the transformation mechanism, theoretical description, numerical simulation of multi-hazard chains, and decision-making. Papathoma-Köhle et al. (2011) analyzed medium-scale multi-hazards by considering disposition alteration and hazard linkage. van Westen et al. (2014) performed a quantitative hazard risk assessment of gravitational processes, including landslides, debris flows, rockfalls, snow avalanches, and floods, in the Barcelonnette area, French Alps. Worni et al. (2014) proposed an integrated method of modeling a typical process of glacial lake outburst floods by combining numerical models of impulse wave, dam breaching, and flood propagation. Chen et al. (2016) implemented a quantitative model of hazard risk assessment integrated with expert opinion in a valley prone to debris flows and floods in the northeastern Italian Alps. Liu and He (2018) simulated a rockslide-triggered multi-hazard chain by using a finite volume method. Recently, a comprehensive method was developed for quantitatively evaluating the risk of a potential debris flow multi-hazard chain (Hu et al., 2018; Hu K. et al., 2019; Hu X. et al., 2019; Luo et al., 2020). Efforts of engineering measures have been made to prevent and control multi-hazard chains, such as those caused by the 2008 Wenchuan earthquake (Xu et al., 2012). The chains are characterized by the so-called cascading effect or domino effect (Delmonaco et al., 2006; Carpignano et al., 2009), i.e., a natural hazard triggers one or more hazards, and the risk spreads over a more extensive space and longer time period. Kappes et al. (2012) pointed out that the interaction among hazards often results in risk amplification, and the means for considering the cascading effects in reducing risk remains a huge challenge.

On June 17, 2020, a rainstorm-induced debris flow event with a volume of 2.4×10^5 m^3 occurred in the Meilong basin, Danba County of Sichuan Province, Southwest China (**Figure 1**). Approximately 1.3×10^5 m^3 of sediment was deposited in the Xiaojinchuan River (XJC), a tributary of the Dadu River, and partially blocked the river channel. Debris-flow deposition forced the river course to move to the left bank, and then the rapid flow strongly eroded the foot of the old Aniangzhai (ANZ) landslide, leading to the reactivation of the 6.2×10^6 m^3 landslide. It is a typical debris flow–outburst flood–landslide chain with intense cascading effects. To stop the chain from developing into a large dammed lake and subsequent catastrophic outburst flood, the government cleared the sediment and recovered the river path. The engineering measures effectively prevented the landslide and eliminated the risk of dammed lake. In this paper, we describe the evolving process of the multi-hazard chain and quantitatively evaluate the cascading consequences with and without controlling measures.

STUDY AREA

The event occurred in Banshanmen town, Danba County, western Sichuan Province, China (**Figure 1A**). It is part of the

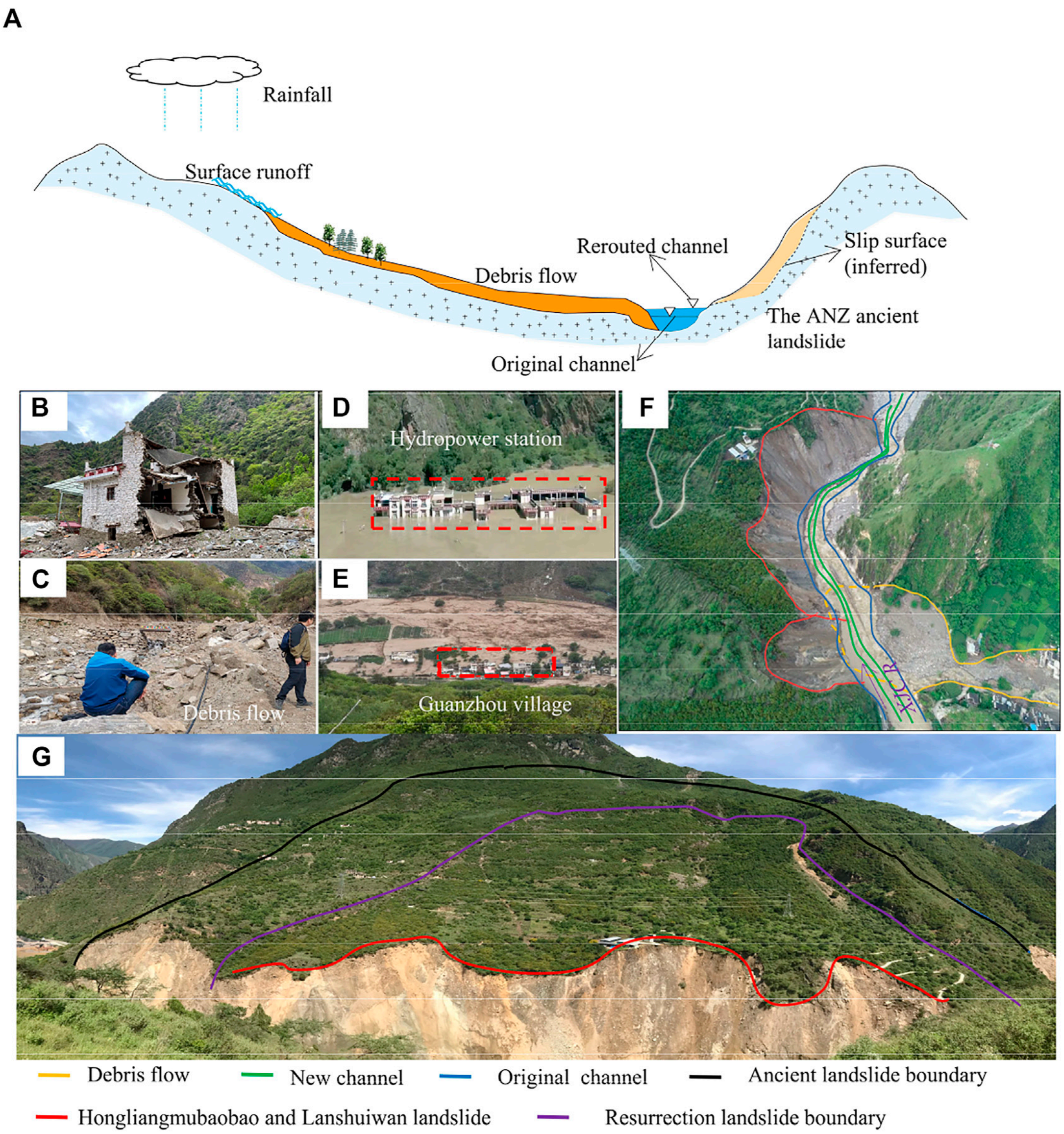

FIGURE 2 | Multi-hazard chain caused by the Meilong debris flow. (b–g) On-spot photos and unmanned aerial vehicle (UAV) images taken in the field survey. **(A)** Schematic of the multi-hazard process; **(B,C)** houses destroyed by the debris flow and debris-flow deposits in the Meilong channel; **(D,E)** the dammed lake and Guanzhou village damaged by the flood; **(F,G)** the ancient ANZ landslide.

transition zone between the Qinghai-Tibetan Plateau and the Sichuan Basin and is part of the alpine valley area with high denudation. The tectonic units of Danba belong to the Songpan-Garze fold system, which is the southern part of the Bayankala Mountains, and the Songpan-Garze fold system is surrounded by the Xianshuihe fault belt, the Longmenshan fault belt, and the South Qinling fault belt. The terrain is generally high in the south and low in the north (Sun and Li 2019). The lithology is complicated and dominated by granite and psammite (**Figure 1B**).

The Meilong basin (**Figure 1C**) is on the right bank of the XJC, a major tributary of the Dadu River. It has a catchment area of 63.2 km^2, and the elevation between 2,125 to 4,783 m. The mainstream channel is 10.2 km long and 30 ~ 60 m wide, with a gradient of 253‰ and bank slope of more than 40°. A debris flow occurred in 1952 (Zhao et al., 2021), and about 84.8×10^5 m^3 (data from the Danba County Water Resources Bureau) of loose material is stored in the basin as supplies to debris flows.

The climate is affected by the Indian monsoon, which causes precipitation of 617 mm per year. According to the rainfall data of the Danba meteorological station over the past 33 years, the rainy season extends from May to September with a total rainfall of more than 460 mm, about 73.3% of the annual rainfall. The daily precipitation is large in July and August, and the maximum

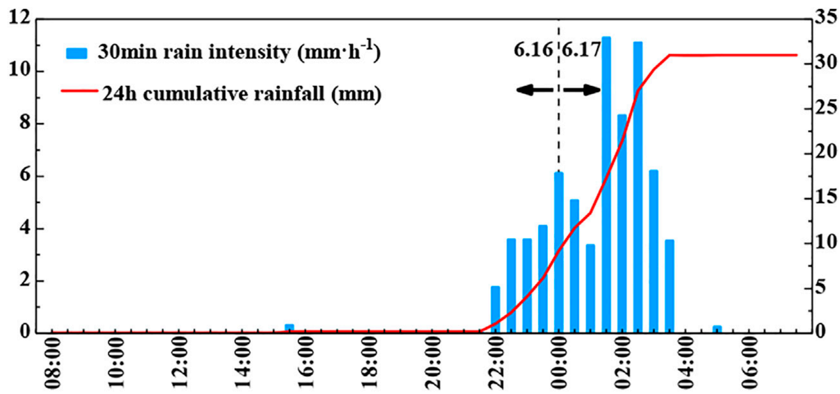

FIGURE 3 | Curve of rainfall at Banshanmen town, Danba County, on June 16 and 17, 2020.

monthly rainfall occurs in September, on average of 109.12 mm (Sun and Li 2019). The rainfall is in short duration and high concentration. From June 8 to 17, 2020, the study area experienced continuous rainfall of 271.6 mm, 1.1 times higher than the historical record since 1951.

"JUNE 17" MEILONG DEBRIS FLOW AND SUBSEQUENT CASCADING HAZARDS

The hazard was a combination of a debris flow, barrier lake (partially damming), outburst flood, and landslide (**Figure 2A**). On June 17, 2020, a debris flow first occurred upstream of Dayi gully (blue dots in **Figure 1C**), a left tributary of the Meilong basin. The flow then entered the XJC and accumulated at the confluence and partially dammed the river to form an ephemeral lake (**Figure 2D**). Two hours later, the dam failed, and the lake outburst increased the river discharge, which changed the river channel. The rerouted channel caused the outburst flood to erode the foot of the ANZ, inducing two small landslides (**Figure 2F**). The loss of mass at the foot and the continuous erosion of the river reactivated the ANZ landslide (**Figure 2G**).

Meilong Debris Flow

The intense rainfall-triggered debris flow initiated at the Dayi gully and ended in the XJC (**Figure 3**). According to the local meteorological bureau, the sudden rainfall started at 23:40 on June 16, 2020. The GPM rainfall data based on satellite remote sensing inversion show that the rainfall intensity reached a maximum of 11.28 mm/h about 2 h before the debris flow. The rainfall intensity was as high as 11.10 mm/h 1 h before the occurrence, and the accumulated rainfall was 30 mm when the debris flow occurred (**Figure 3**). Sediment was quickly eroded along the flow path, and the main area of erosion is a Quaternary accumulation terrace near the Dayi gully (**Figure 1**). The debris flow lasted for approximately 40 min with a peak velocity of 8.2 m^3/s (Zhao et al., 2021), transporting 2.4 × 10^5 m^3 of material and forming a 3.0 × 10^4 m^2 deposit fan. Approximately 1.3 × 10^5 m^3 of sediment was transported into the main river, and the fan was approximately 1.1 × 10^5 m^3 (Hu et al., 2020). According to the field investigation, the flow is 20–80 m wide and 3 m in depth, with boulders ranging between 0.1 and 0.5 m in diameter, up to the maximum of 5 m (**Figure 2C**). Several houses were buried and damaged by the debris flow (**Figure 2B**).

Barrier Lake and Outburst Flood

The debris flow and subsequent small landslides deposited large amounts of sediment in the XJC, forming a barrier lake of 200 m long, 50 to 100 m wide, and 8 to 12 m high. According to remote sensing images, the maximum area of the lake was 1.45 × 10^5 m^2 (**Figure 1D**), and the submerged area was 1.13 × 10^5 m^2. The surface was 4.6 m higher than the river and flooded the first floor of the ANZ station (**Figure 1D**). The volume of the lake was 6.62 × 10^5 m^3. Threatened by such a dam that is usually unstable and has a shorter life (Fan et al., 2020), more than 21,200 people in the downstream towns were evacuated. The barrier lake completely breached only about 2 h later, and the flooding process began at 12 p.m. and ended at 4 p.m. The discharge of the outburst flood is 492 m^3/s, the same order of magnitude as the seasonal flood flow, but the dam moved the river channel 20 m to the left. The flood damaged No. 303 provincial road (S303 in **Figure 4**) on the left bank and seriously eroded the foot of the ANZ. In addition, many houses, a large area of farmland, and about 20 km of roads were flooded downstream, and the flooded area of Aniangzhai village was approximately 0.8 km^2. The outburst flood induced six landslides, among which the largest landslide was the ANZ (Yao et al., 2020).

Reactivation of the ANZ Landslide

The ANZ is a bedrock landslide with an area of 1.4 km^2 and a thickness of 50 m. It occurred 120 years ago and blocked the river. In recent years, the landslide has crept slowly, with occasional cracks appearing in buildings and farmland on the landslide. Satellite images also showed some small-scale historic landslides. Nonetheless, the ANZ remains stable on the whole. However, the outburst flood erosion of the slope foot has caused two small landslides, the Hongliangmubaobao landslide and

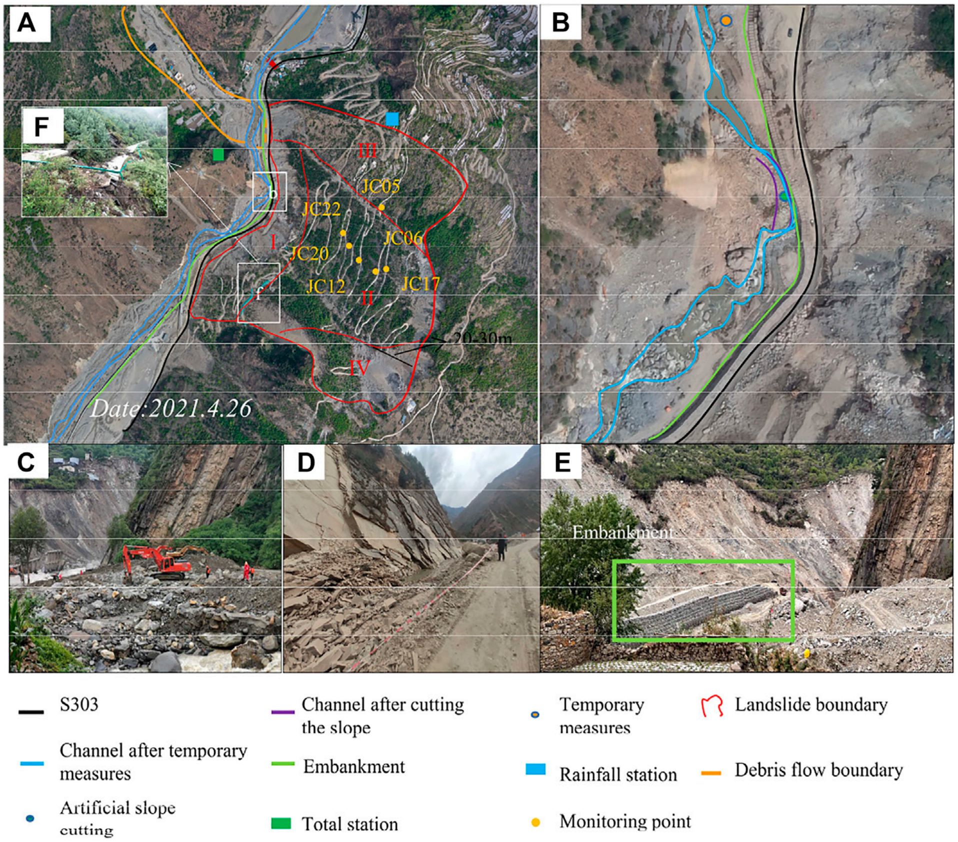

FIGURE 4 | Changes in the Meilong valley around the ANZ landslide and engineering measures after the debris-flow event. **(A)** Detailed characteristics of the reactivated ANZ area and emergency monitoring scheme. (I: front collapse zone, II: main deformation zone, III: upstream deformation zone, IV: downstream deformation zone). **(B)** Influence of engineering measures on channel evolution. **(C)** Temporary engineering measures: the excavator dredging the river. **(D)** Workers blasting the slope. **(E)** Temporary embankment. **(F)** Road falling apart.

Lanshuiwan landslide, which formed a free face about 60 m high. The instability of the foot and the continuous erosion of the river induced the ANZ to reactivate and slide.

RIVER EROSION AND LANDSLIDE DEFORMATION

Sediment usually forms dams and blocks rivers after landslides or debris flows (Costa and Schuster 1988; Hermanns et al., 2004). If the dam breaks, the outburst flood can cause serious harm downstream (Fan et al., 2012). Dams can be divided into complete dams and partial dams depending on the volume and composition of debris flows, which cause different changes in river morphology. If the riverbank is part of the diversion channel, the narrowing flow accelerates the bank erosion (Costa and Schuster 1988; Abidin et al., 2017). The Meilong debris flow formed a partial dam. After the dam broke, the flood altered the position of the channel and intensified the erosion on the left bank, leading to landslide reactivation.

The Lanshuiwan and Hongliangmubaobao landslides in front of the ANZ have moved 3–15 m with a volume of 2.76×10^6 m^3 entering the channel (**Figure 2F**). There was obvious deformation at the back and some cracks in the middle (**Figure 3G**). The road on the landslide was destroyed with a vertical dislocation of 5–14 m (**Figure 4F**). The horizontal and vertical displacement at the foot are 15–20 m and 15–25 m, respectively; and a large number of fractures formed near the downstream boundary. The displacement at the back of the landslide reached 20–30 m (**Figure 4A**), an increase of 5–10 m compared to August 20, 2020. A new channel is cut at the foot of the landslide, and the current channel becomes wider than ever (**Figure 2F**). Now the government has carried out engineering measures, including dredging (**Figure 4C**), changing the channel position (**Figure 4B**, **Figure 3D**), and building embankments (**Figure 4E**).

A ground-based radar for emergency monitoring detected the accelerating deformation of the landslide from June 18 to August 20, 2020. Rainfall and river discharge were monitored to investigate the landslide variability. Monitoring points 2, 23, 20, and 9 were set up in front collapse zone I, main deformation zone II, upstream deformation zone III, and

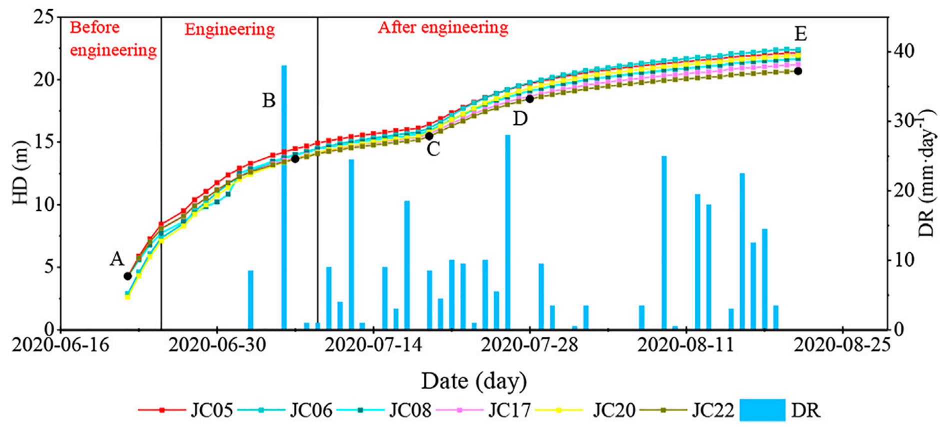

FIGURE 5 | Landslide cumulative surface displacement and monitoring daily rainfall (DR: daily rainfall; HD: horizontal displacement).

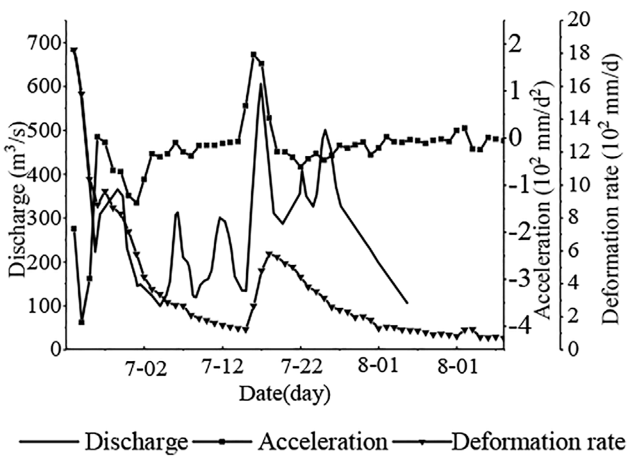

FIGURE 6 | Deformation rate and acceleration of monitoring point JC22 and river discharge. The river flow data are from the Guanzhou power station, whose location is shown in **Figure 1D**. The river flow data in **Figure 6** are the same as those in **Figure 7**.

downstream deformation zone IV, respectively. Six representative points were selected to represent the deformation of the landslide (**Figure 4A**). We find that landslide displacement is greatly affected by river discharge and engineering (**Figure 5**). The maximum and minimum velocity and acceleration of the landslide motion ranged from 75 mm/h and 16.46 mm/h^2 to 8.74 mm/h and 0.13 mm/h^2, respectively, before and after engineering measures (**Figure 6**). Moreover, the coupling of rainfall and fissures within the ANZ landslide accelerates the displacement rate, which is consistent with the new development of fissures in its back (**Figure 4A**). The ANZ landslide experienced four stages: two rapid displacements (A-B and C-D) and two slow displacements (B-C and D-E). After the dam failed, the outburst flood eroded the foot of the landslide, resulting in the rapid displacement (A-B), with a sliding distance of 12 m in 10 days. As the river moved away from the foot (B-C), the displacement gradually slowed down to 3 m in 15 days. A change in the water level reduced the pore water pressure of the soil beneath the landslide and caused the stress redistribution of the whole slope (Rahardjo et al., 2001). The dissipation process of pore water pressure resulted in changes in soil strength and accelerated the displacement of the landslide, which was 4 m in 8 days (C-D). The deformation rate of the landslide controls the development of excess pore water pressure, and the excess pore water pressure determines the change in shear strength of the soil. When the reduced sliding resistance is less than the sliding force, the landslide slides, and then the landslide reaches a new stress equilibrium. The process is controlled by the dissipation of pore water pressure, which lags behind the change in the channel position, and in this case, it lagged 15 days. Then, the landslide entered the slow displacement stage (D-E) again, with a displacement of 4 m in 26 days. As shown by the displacement curve, the channel position directly affects the stability of the landslide but lags behind the change in river position.

In this study, we refer to the seepage monitoring model to consider the hysteresis effect.

$$v = v_0 + \frac{\tau - \tau_f}{m} t = v_0 + \frac{\tau - \left\{c' + \left[\sigma - \left(u_w + p\left(Z, t_{diff}\right)\right) \tan \phi'\right]\right\}}{m} t$$

where v is the velocity of the landslide (m/s); v_0 is the initial velocity of the landslide; τ is the shear sliding force acting on the sliding surface (kPa); τ_f is the resistance along the sliding surface (kPa); t is time (s); σ is the total stress (kPa); c is the cohesive force (kPa); ψ is the internal friction angle (°); u_w is the pore water pressure (kPa); c' is the effective cohesion (kPa); ψ' is the effective internal friction angle (°); and p (z, t) is the pore water pressure increment at time t and depth z of the sliding block (kPa).

Therefore, under the limit equilibrium state, the rise and fall of pore water pressure on the sliding surface will lead to the acceleration ($V > 0$) or deceleration ($V < 0$) of land sliding.

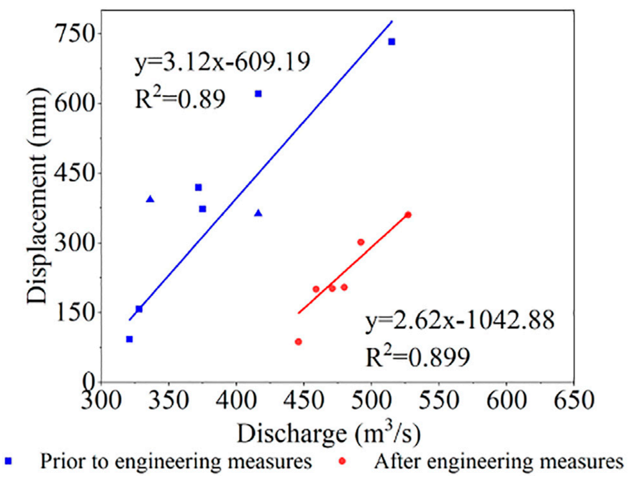

FIGURE 7 | Relationship between river discharge and horizontal displacement of the landslide before and after the engineering measures were implemented. Triangle data are from Zhao et al. (2021).

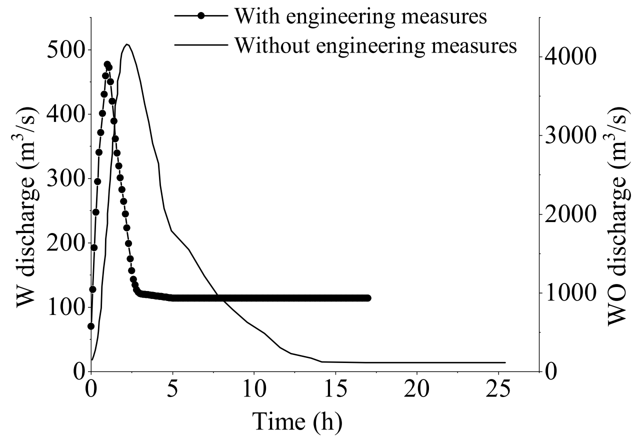

FIGURE 8 | Discharge hydrograph of the outburst floods with and without engineering measures (W: with engineering measures, WO: without engineering measures).

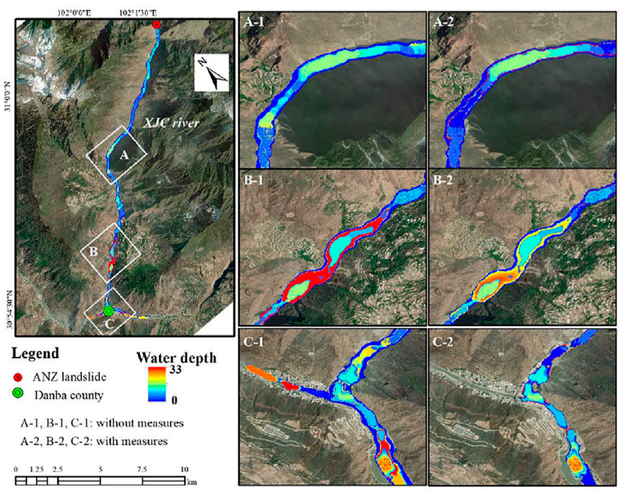

FIGURE 9 | Spatial distribution of the computed maximum flow depth. A-1, B-1, C-1: without engineering measures, A-2, B-2, C-2: with engineering measures.

When the river flow increases, the pore pressure rises, so the landslide movement accelerates (**Figure 6**). However, the pore water pressure increment generated by rainfall and river flow changes needs time to act at the sliding surface. This lag time t_{diff} is closely related to the hydraulic diffusion coefficient and the landslide thickness. Thus, it indicates that the landslide displacement lags behind the change in river discharge (**Figure 5**).

To describe the influence of channel position on the landslide stability, we draw a scatter plot according to the relationship between river discharge and landslide displacement in the two stages (**Figure 7**), which shows a good linear relationship; and the influence of river discharge on landslide stability has been greatly decreased by engineering measures. Two straight lines ($y = Ax + B$) were obtained by fitting the scattered points, where A represents the ability of discharge to influence the landslide displacement, and B/A represents the minimum discharge required to generate displacement. Before the engineering measures were implemented, landslide displacement occurred when the river flow was 126.76 m^3/s (the blue line in **Figure 6**), but the threshold for displacement increased to 398.05 m^3/s (the red line in **Figure 6**) after the engineering measures were implemented. The ability of river flow to affect the landslide before the engineering measures were implemented was 1.19 times (the ratio of the blue line's slope to the red line's slope in **Figure 6**) that after the engineering measures were implemented.

The fluvial erosion due to the river channel change has the greatest influence on the stability of the landslide. Therefore, the most significant impact of the engineering measures is to change the position of the channel, which prevents erosion at the foot of the landslide, thereby preventing a reduction in slide resistance. The change in the channel position also reduces the ability of discharge to affect landslides.

HAZARD ASSESSMENT WITH AND WITHOUT THE ENGINEERING MEASURES

Engineering measures lowered the risk or probability of the hazard reoccurring. To directly represent the impact of engineering measures, we calculated the flow duration curve without engineering measures and the hazard assessment before and after engineering measures (**Figures 8**, **9**).

The total volume of the ancient ANZ landslide is estimated as 6×10^6 m^3, which would form a dam at least 100 m high and impound water of 8.2×10^8 m^3. Chen et al. (2015) proposed the hyperbolic model of soil erosion rate and the circular sliding surface method with the lateral expansion of the gap. The governing equations are solved using a numerical method that allows simple calculations in Excel 2007 spreadsheets. Using the DB-IWHR dam flood analysis program, the maximum flow at the barrier dam without engineering measures was 4,180 m^3/s (10 times as much as after engineering measures were taken), and then the flow gradually decreased. Approximately 6 h after the outburst, the flow attenuated to 1,536 m^3/s, attenuating by approximately 63.1%; approximately 11 h after the outburst, the flow attenuated to 413 m^3/s, attenuating by approximately 89.7% (**Figure 8**).

With the two discharge hydrographs corresponding to natural evolution and engineering intervention, a computational program developed by Ouyang et al. (2013) is applied to simulate the propagation of the outburst floods. The governing equation of flood movement is the diffusion wave equation obtained by simplifying the depth integral of Navier-Stokes equation and ignoring the convective term of momentum equation, and then solved by a first-order upwind finite difference scheme. The basal friction relationship is the traditional Manning's model. The flood hazard is related to destructive power of a flood such as flow depth, velocity, or impact force. We use the maximum flow depth as the proxy of the flood hazard (**Figure 9**). The flood will reach the city of Danba after passing the confluence of Dajinchuan and XJC rivers and move upstream along the Dajinchuan River if without engineering measures. The inundation area of the city will be approximately 130,000 m^2 and the maximum runoff depth reaches 33 m (**Figure 9**-C-1). The area with the maximum flow depth >10 m accounts for 16.19% of the total area. However, due to the timely engineering measures implemented by the government, the dam-break flood propagated downstream of the Dadu River and did not reach the Danba city upstream (**Figure 9**-C-2). The area with the maximum flow depth >10 m only accounts for 6.79% of the total area, a reduction of 9.4% compared with no engineering measures.

DISCUSSION

Previous studies on multi-hazard chain have emphasized the role of engineering measures (Gilbuena Jr et al., 2013; Bouwer et al., 2014). Mechler (2016) apply CBA (CBA is a major decision-supporting tool used by governments to organize and calculate the societal costs and benefits) to hazard risk reduction (DRR), which believes that the short-term method to break the hazard chain is mainly using engineering measures. On October 10, 2018, a landslide hazard chain occurred at Baige, Jiangda County, Tibet, China on the Jinsha River. In the Baige multi-hazard chain, the Chinese government decided to dig a spillway 33 m deep and 10.89 m wide at the bottom and 120.57 m wide at the top. The spillway was completed 2 days before the breaching of the dam. Later, this was shown to be extremely effective (Zhang et al., 2020). The Hongshiyan landslide dam formed by the 2014 Ludian earthquake in Yunnan Province, China also adopted a similar mitigation measure as the Baige landslide hazard chain (Shi et al., 2017). Similar to previous studies, the Chinese government also took engineering measures to change the channel position and thus truncate the Meilong multi-hazard chain.

The influence of channel position on landslide deformation is important. In this paper, the main factor affecting the stability of the ANZ landslide is the erosion of the slope foot by flood. Therefore, to quantify the influence of flood erosion on the stability of ANZ landslide, Janbu method was adopted to calculate the stability of landslide. The Janbu method assumes that the force is applied to one-third of the height of the block, and each block satisfies both static equilibrium conditions and limits equilibrium conditions. The slip zone also satisfies the torque equilibrium condition.

The stability factor of the ANZ after engineering was 1.09 by assuming that $\gamma = 20$ kN/m^3, $\varphi = 20^\circ$, and c = 19 kPa (Yu, 2018). If the river continues to erode horizontally to 17 m, the stability factor would drop to 0.93, and the landslide would slide down. When we returned in April 2021, the landslide had not slid down as a whole and was stable. Therefore, we can express that the government's engineering measures delayed and reduced the acceleration of landslide deformation, stopped the multi-hazard chain, and protected the safety of downstream residents, especially Aniangzhai village to Danba County along the XJC River.

CONCLUSION

On June 17, 2020, the Meilong debris flow triggered a multi-hazard chain, including the formation of a dammed lake, a subsequent outburst flood, and reactivation of the ANZ by toe erosion. Without intervention, the landslide could trigger a larger multi-hazard chain, threatening the downstream area. Therefore, the government implemented timely engineering measures. By analyzing the blocking effect of engineering measures and quantitatively evaluating the cascading consequences of the multi-hazard chain with and without artificial intervention measures, we draw some conclusions.

The landslide had a large displacement before the engineering measures were implemented; and the measures have changed the river channel 20 m away from the slope foot and prevented the slope erosion. The change in the channel position also led to the gradual decrease in pore water pressure and the decrease in total stress at the foot of the slope, resulting in the redistribution of stress and a short rapid displacement of the landslide. This phenomenon lagged behind the change in the channel position due to the slow dissipation of pore water pressure. That is, in the first stage, the water level of the river inundated the slope foot. This means lateral support of flooding water while there is severe erosion at the same time. If this river support is withdrawn by displacement of the river and the water level drops, the seepage pressure of the dissipating water at the foot will at first decrease the stability at the foot and hence the stability of the entire landslide. However, drainage at the foot also means a drawdown of the water table all over the landslide and an increase in instability.

We calculated the stability of the landslide by the Janbu method. The safety factor of the ANZ is currently 1.09, but it will drop to 0.93 if the river continues to erode the foot of the landslide by 17 m. Without engineering measures, a 100m-high dammed lake with a capacity of 8.2×10^8 m³ could be formed, and the flood would reach Danba city after passing the intersection of rivers and flowing up the Dajinchuan River basin without engineering measures, which would be devastating to downstream areas.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

LN: Formal analysis, Writing—Original Draft; KH: Supervision, Conceptualization, Funding acquisition; ZW: Writing—Review and Editing; HL: Data Curation; HQ: Data Curation; XZ: Visualization; SL: Funding acquisition.

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Students Understanding of Earthquakes and Tsunamis in High Risk Areas

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Population growth and spread have increased human exposure to natural hazards and potential disasters affecting people's quality of life. This situation is especially manifested in marginalized or vulnerable areas. Moreover, within such vulnerable areas, children are especially affected, and are, at the same time, considered to be agents of change. However, children's voices have been scarcely considered for disaster risk reduction planning, and science education has not widely addressed these ideas. This study explores the understanding of earthquakes and tsunamis by children living in high-risk areas of Chile during a learning unit and according to their geographical zone. The study was part of a context-based science education learning unit. One hundred and two students from four schools used explanations to draw and write the causes of the risk situation, revealing their understanding of each phenomenon. The results show most students attributed earthquakes to the Tectonic Plates Theory while holding ancient scientific ideas about tsunami causes, for example, some explanations were based on air pressures. More sophisticated reasoning was found at the end of the learning unit, advancing their understanding of hazards promoted by the science education of the learning unit. The relevance of context-based science education for disaster risk reduction is discussed, especially for the cases of children with animistic - transferring human needs and attributes to non-animated entities- or fatalist understandings of the phenomena. The scientific understanding perhaps promotes empowerment and action-based choices for safety. Furthermore, the argument for policy curriculum design in primary science education for mitigating disasters is discussed.

Keywords: explanation, earthquake, tsunami, science education, students-basic education, reasoning, children

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INTRODUCTION

Population growth and spread has increased human exposure to natural hazards. Although there are new technologies to support the information about hazards, the impact of disasters continues to advance around the globe with accelerating consequences (Delicado et al., 2017). Disasters affect people's quality of life, especially within marginalized or vulnerable groups, such as women or children (Ronan et al., 2015; García, 2016; Delicado et al., 2017). Indeed, children suffer the devastating consequences of disasters because of the loss of daily routines, delayed academic progress, missed social opportunities in a critical development period, and increased exposure to various life stressors due to their partial or total dependence on adults (Peek, 2008). The Sendai framework for disaster risk reduction focuses on all community participation for this objective, which led to a child-centered disaster risk reduction approach to promote their agency in building individual and community resilience (Wachtendorf et al., 2008; Aitsi-Selmi et al., 2015). There is a need to shift from disaster recovery to prevention, focusing on peoples' education for the primary goal of disaster reduction; the development of safety culture (Izadkhah, 2005). Reducing the risk of hazardous events can be achieved by helping children and families to learn exposure and vulnerability-risk-reduction strategies (Ronan et al., 2015). Educational programs can decrease children's vulnerability and promote personal, family, and community resilience (Finnis et al., 2004; Wachtendorf et al., 2008; Muttarak et al., 2013). Nonetheless, children's voices have been scarcely considered for disaster risk reduction planning (Freeman et al., 2015; Vásquez et al., 2018). Usually, they have been portrayed as passive, helpless victims or vulnerable aid recipients (Tanner 2010). Still they can play an active role in recovery and rebuilding; thus, recognizing their strengths and listening to them is crucial (Freeman et al., 2015).

There is evidence that understanding the natural phenomena that might become a local disaster is crucial for disaster risk management, empowering communities, and educating people to prevent possibly resultant negative impacts (de Guzman, 2003; Wesely, 2021). Acquiring knowledge on natural phenomena and its application in emergencies is the most effective way for preventing disasters or mitigating their effects (Izadkhah, 2005; Torani et al., 2019).

Studying children's understanding of phenomena that might lead to disasters is an increasing area of research interest (i.e., Aydin, 2011; Leather, 1987; Torani et al., 2019; Tsai, 2001). Although, review reports (Ronan et al., 2015; Torani et al., 2019; Cabello et al., 2021) have shown that few studies have successfully connected curriculum-based formal science education with disaster risk reduction regarding understanding of those phenomena (e.g., Cahapay and Ramirez, 2020; Shoji et al., 2020; Tyas & Pujianto, 2020). Science curriculums can be transformative tools for students to view themselves as active in their role within current socio-political structures (Guerrero & Torres-Olave, 2021). Educational disaster-reduction initiatives often have dual orientations; to motivate children and families to act to be prepared to face disasters or to teach students about the science of natural phenomena (Izadkhah, 2005). Our initiative studies the second of these choices, considering that promoting educational programs must support teachers in the program implementation, because by only creating resources for voluntary use without guidance and assessment it is unlikely to lead to high uptake levels (Ronan et al., 2015).

Children need to understand natural hazards first to be prepared to face risk events (Finnis et al., 2004); scientific literacy is requisite but not guaranteed for disaster preparedness (Cahapay and Ramirez, 2020). Their understanding and reasoning capacities need to be explored because the ideas about causes and consequences of disasters are linked to preventing consequences via action-based safety choices (McDonald et al., 2019). However, no study has explicitly focused on cognitive aspects such as science literacy to explain student's disaster preparedness variability (Cahapay and Ramirez, 2020). The studies of curriculum materials on natural hazards have shown to be oriented to lower cognitive skills such as recall of knowledge, not on higher-order abilities (Cahapay and Ramirez, 2020), such as the act of phenomena explanation. It is a matter of interest because children's understanding of the phenomena, its causes, and local consequences, can build intergenerational capabilities for risk management and personified vectors of hazard education to those around them (Finnis et al., 2004; Izadkhah, 2005; Muzenda-Mudavanhu, 2016; Torani et al., 2019).

Understanding and Knowledge Construction

Understanding the geological aspects of Earth science is a complex process because of the multi-dimensional and hierarchical nature of the subject (Blake, 2005). Contextual factors matter in the understanding of phenomena. For instance, Bakopoulou et al. (2021) assume that the density and distribution of geodynamic phenomena in the time and place where people live can determine the form of ideas they hold. Learning about theories collectively is one of the components of developing scientific reasoning, defined as intentional knowledge-seeking and coordination of theory and evidence (Kuhn, 2002).

Scientific reasoning is a cumulative and cyclical process (Zimmerman, 2007). Usually, children's reasoning starts from intuitive knowledge construction to progressively create precursor models of why the phenomena occur. Precursor models are "cognitive schemata compatible with scientifically appropriate knowledge since they are constructed based on certain elements pertinent to scientific models, which have a limited range of application, and which prepare children's thinking for the construction of scientifically appropriate models" (Ravanis et al., 2013 p. 2259). Students often use mental structures as intermediate stages in science education to understand and interpret a phenomenon, progressively showing their knowledge acquisition (Vosniadou & Brewer, 1992; McDonald et al., 2019). In this knowledge construction, children's ideas operate as synthetic alternative inputs representing the integration of new information into their initial ideas, advancing into more complex explanations of concepts and models (Libarkin, 2003).

Children's Ideas About Earthquakes and Tsunami

Children's ideas about earthquakes have been explored in diverse geographies, although tsunami ideas are less researched so far. Regarding earthquakes, in the United States, the students know the phenomena before formal instruction, but most do not know its cause. Misconceptions were persistent even with formal science instruction. Particularly, weather conditions as causes of earthquakes or defining volcanoes and earthquakes as the same or similar phenomena revealed that classroom instruction did not guarantee understanding the topic (Ross and Shuell, 1993).

Similarly, in France, Allain (1995) showed that students connect causally, and more often earthquakes to a volcanic activity, the internal structure of the planet, atmosphere, and less frequently to tectonic causes or faults; furthermore, causal connects were made with Earths' rotational movement, human causes, and extra-Earth ideas such as meteorites. Singaporean students related earthquake phenomena mainly to magma activity (Wang et al., 2009), while in Puerto Rico, Mejías & Morcillo (2006) found that six percent of secondary students related earthquakes to Tectonic Plates Theory (TPT), with some confusion between the concepts of "layers" and "plates." The complex interaction between personal beliefs, including religious, ancestral, or family beliefs; and scientific knowledge is generally known (Berkes, 2008). In Mexico, primary students hold causal ideas related to Aristotle's ancient views as "Earth accommodation" or Neptunian as "products of volcano eruptions' (Rodriguez-Pineda & Faustinos, 2017), which are considered nowadays for some authors as misconceptions (Francek, 2013) or alternative ideas (Licona et al., 2013; Rodriguez-Pineda & Faustinos, 2017).

Regarding tsunamis, Taylor and Peace (2015) found that Indonesian children's religious beliefs shaped their worldviews and were used to explain causes of floods; God, to fate (as something that God would determine) or human recklessness, demonstrating a worldview in which the spiritual world does affect the physical world. Indeed, the participants viewed prayer as an action to prevent flooding and reduce its risk. Adyoso and Kanegae (2012) show that without curricular education, 40% of children attributed tsunami to Gods' wrath, 36% to man-made activities, and 6% view it as a natural phenomenon, while with education, the percentages were 38% natural phenomenon, 31% God's wrath and 22% man-made activities.

Concerning the change of ideas, students combine scientific and mythological ideas, using three cognitive strategies to solve perceived incongruencies; to accept the scientific theories and reject their world vision, to accept the scientific ideas but keep their world vision or keep their ideas and ignoring the scientific ones (Tsai, 2001). Likely then, by embracing indigenous explanations one might facilitate understanding of scientific models of the phenomena when complementarities are established, I.e., by respecting other ways of knowledge creation apart from science, such as oral or ancestral traditions. Indeed, there is no need to replace one system of beliefs, but rather to enrich each other. It also reinforces the right for indigenous people to explain using their own words (King & Goff, 2010).

Additionally, students' attitudes towards learning science are positively associated with risk perception, perceived coping ability, knowledge about disaster mechanisms and response, and propensity to respond appropriately. Still, although years of schooling on disaster preparedness are positively associated with survival rate, Shoji et al. (2020) point out that the school curriculum determines disaster preparedness and response because it is more important what people learn and not how long they spend learning it. Thus, they suggest science education would reduce the mortality risk of children by influencing their knowledge, perception, and behaviors about disasters.

Regarding what is observed of children's ideas, two alternative trends are seen: students lacking scientific knowledge or considering their ideas as sources for building models. For instance, a study conducted with 12–13-year-old Greek students showed more than half of them attribute earthquakes to two plates within or underneath Earth, and 24.2% added information about "collision." The authors indicated their result depicts students' insufficiency, ignorance, or unsuitable training to (a) correlate surface phenomena such as earthquakes to the inner Earth, (b) tackle with process orientated thinking, and (c) search for the cause of the phenomena (Bakopoulou et al., 2021). The imprecise ideas of the students can also be seen as a precursor model, based on some elements of a scientific model, but still holding room for improvement through learning (Ravanis et al., 2013). For instance, about the forementioned conclusion, Vergara-Díaz et al. (2021) found improved students' ideas about Earth Sciences after model- and inquiry-based science instruction.

However, a difficulty arises with scientific education when many students use scientific terms such as magma, mantle, core, lithosphere, plates, or plate tectonics, which they cannot explain, meaning that incorporation of scientific terminology into an explanation does not necessarily imply understanding. Thus, although high school students are exposed to geoscience concepts and terminology, most of them demonstrate an incomplete understanding of the phenomena (Libarkin et al., 2005). Research in the effects of education for disaster risk reduction in children's understanding of the phenomena lacks follow-up of adaptive coping following hazard events. It relies mainly on surveys, interviews, self-reports (Ronan et al., 2015).

To address and investigate further the problem described above, we have merged distinct learning products; we explored student's understanding of tsunami and earthquakes, going beyond incorporating new vocabulary in order to interpret their comprehension of the phenomena through their expressed reasoning. Thus, the present study–through context-based science education - focuses on constructing precursor models using drawings and written explanations of earthquakes and tsunami in schools which are exposed to natural hazards. This approach helps students make sense of abstract phenomena through their conceptualization of causes and awareness of their consequences (Bennett et al., 2007), contributing to disaster risk reduction aided by science education. The research questions were: RQ1. Which are the initial explanations of 4^{th} graders about earthquakes and tsunami? RQ2. Are there differences between the geographical zones? RQ3. To what extent do 4^{th} graders' scientific reasoning progress during a pedagogical unit? The findings of this study might be relevant to scholars, curriculum developers, researchers, and teachers.

METHODS

This study considered the school's exposure to natural hazards as a starting point to exploring fourth grader's explanations about the causality and consequences of earthquakes and tsunami in two formats: drawn and written. The aim was to characterize children's understanding of phenomena - earthquakes and tsunamis - that might become a disaster in their territories, their understanding of specific causes; then analyzing the scientific reasoning expressed in precursor models in context-based science education.

A participatory and pragmatic paradigm was followed (Yvonne Feilzer, 2010). The study involved schoolteachers in the decisions and aimed to help the educational school communities at risk to be aware of the hazardous situation in which they live. Moreover, the study pursued empowering children to be active in disaster risk reduction through raising their ideas about the phenomena and opening opportunities to express and further sophisticate their understanding.

The schools were selected because of their proximity to a disaster-risk zone, near the San Ramon's active geographical fault in the capital of Chile, Santiago - which exposes the community to a disaster caused by earthquakes. Other schools were located near the tsunami flooding risk area in the Valparaíso coastal region of Chile.

The sampling was purposive (Patton, 2001), selected typical cases in the two extreme geographic conditions. The participants (n = 102), that completed at least one task, were aged between 8 and 9 years and had the permission of their parents and their consent to join the study. They belonged to four classes, two in the coastal zone and two in the capital. As the class sizes were not equivalent, we grouped them according to the zone criteria to run the quantitative analysis; coastal zone (n = 39), capital zone (n = 63). Moreover, as the students completed the learning tasks voluntarily, the numbers were not equivalent within the classes. Descriptive results were expressed in percentages to have a standardized approach. The Ethical Board at Pontificia Universidad Católica de Chile approved the research procedures.

The selected learning unit was part of the compulsory national curricula for fourth grade. The study was conducted between 2019 and 2021. Three classes participated at the end of 2019, while during 2020, the schools selected were closed because of the pandemic. The fourth class -needed to complete the sample-, was included in 2021 when the school reopened. The teachers taught "The internal dynamics of Earth" learning unit in 18 h of work distributed throughout 4 weeks approximately. The contents included by the mandatory curricula were; Earth structure models, Tectonic Plates Theory, dynamics of earthquakes, tsunami and volcano eruptions, security, and evacuation planning. The teachers received the pedagogical materials and support for designing context-based science education. This approach includes "using concepts and process skills in real-life contexts that are relevant to students from diverse backgrounds" (Koballa et al., 2005, p. 75). The teachers chose the lesson type and resources among; textbooks, manipulative material such as clay, Tectonic Plates puzzle, videos about the phenomena in their territories, simulations, augmented reality, posters, maps of hazards, and the school security plan to adapt or create. However, they had to authorize the researchers' interviews leading to drawings and written worksheets of the project as learning samples, at the beginning and end of the learning unit to collect and compare the datasets, and allow at least one lesson be recorded.

A mixed-methods approach was used, combining qualitative and quantitative methodologies. The methods to generate the datasets were based on: (i) drawing representations, (ii) written worksheets, (iii) interviews, and (vi) lesson recording. This article reports findings from drawings and written explanations because they directly relate to the participant's conceptual understanding of the phenomena. The specific prompts for eliciting drawn explanations were: "Represent or draw in this sheet your explanation about "Why does the ground move? What do you think this is due to? Why do big sea waves reach the town? What do you think this is due to?" (in Spanish: *R*epresenta o dibuja en esta hoja tu explicación sobre ¿por qué se mueve el suelo? ¿A qué crees tú que se debe esto? ¿Por qué hay grandes olas que llegan a la ciudad? ¿A qué crees tú que se debe esto?). Similarly, for eliciting written explanations, the prompts were "please explain: Why does the ground move? What do you think this is due to? Why do big sea waves reach the town? What do you think this is due to?" (in Spanish: *E*xplica a continuación: ¿por qué se mueve el suelo? ¿Por qué hay grandes olas que llegan a la ciudad? ¿A qué crees tú que se debe esto?). None of the questions included the phenomena name "earthquakes" or "tsunami" because the first step of the learning progression assessment in explaining is the students' identification of the phenomena by its name, according to Yao and Guo (2018). The initial measurements were applied during the first week of the learning unit. The final ones were when the teacher ended the unit, usually in the fourth week, following the regular science lesson plan. The drawings were coded using a rubric conceptually validated to analyze student's understanding expressed in explanations based on a scientific theory. It has three advancing levels - and a level 0 that considered missing data- (Cabello et al., 2021). The rubric is described as follows:

- Level 1: Sensory level of understanding. The reasoning operates based on elements within the student's perception of their senses. The phenomena are represented by their consequences, usually beneath the surface or the sea surface (tsunami case), not above.
- Level 2: Causal understanding includes drawing of elements beyond the sensory experience, usually connected with tectonic plates theory but not representing the dynamic mechanisms.
- Level 3: Causal understanding with dynamic mechanisms of tectonic plates theory. The drawing of representations includes non-visible theories or non-perceived elements to explain processes.

The written explanations were analyzed with Yao and Guo's Scientific Explanation Progression Assessment (SEPA) (2018), with five inclusive stages described as:

- Stage 1: The student identifies the phenomenon, it has a single or a few variables, but their relationship is simple; the changing pattern conforms to everyday experience.

- Stage 2: The student additionally adds support for their explanation.
- Stage 3: The student additionally uses the critical variables as the clue for choosing scientific concepts, laws, theories, and or principles; makes a primary logical connection between idea, data, and phenomenon, through generalization, induction, or simple causal reasoning but with incorrect components.
- Stage 4: The student performs as in stage 3 but without incorrect or incomplete elements.
- Stage 5: The student additionally develops a causal chain or clarifies the mechanism that connects phenomenon, evidence, and theory through scientific reasoning, including isolation and control of variables, correlational reasoning, probabilistic reasoning, etc.

The written answers also were analyzed using qualitative content analysis to systematically categorize textual data (Miles & Huberman, 1994), using the causal categories by Mejías and Morcillo (2006).

- 1. Ancient science, such as Aristotle's conceptualization of "Earth accommodation" or Seneca's ideas about "trapped gases moving between internal Earth cavities," which are present across cultures because of their sensory origin (Pozo & Gómez, 2001).
- 2. Tectonic plate theory's current scientific knowledge is related to geological fault or tectonic plates.
- 3. Volcanic eruption as the cause of earthquakes and tsunamis.
- 4. Anthropogenic actions include earthquakes and tsunami caused by human deforestation, contamination, and extraction.
- 5. Religious beliefs, such as earthquakes or tsunamis as God's punishment, faith or prayer can stop or prevent an earthquake.
- 6. Animistic; transfers human needs and attributes such as intentions, willingness, decision-making, emotions such as anger, revenge, etc., to Earth. "Animism" is an instinctive, primary mechanism of thinking development based on analogical transference (Piaget, 1933).
- 7. Astronomy, such as meteorites, Earth-Sun-Moon alignment.
- 8. Atmospheric or climatic factors, such as the change from a sunny day to a rainy.

Three research assistants coded the drawings and written answers independently from each other. They received training on the instruments by the main researcher and started applying to a small sub-sample data set. Several discussions followed, until reaching a consensus. Once the inter-rater reliability was over 90%, the team analyzed the rest of the material as blind peers. Thus, at least two raters analyzed each drawing and written explanation to enhance reliability. Weekly meetings allowed calibration of the group, and the four members solved the few divergences found. Thus, the final score was equal between two coders or determined in group agreement. The quantitative analysis explored the possible differences in children's explanations and models at the learning unit's beginning and end, and according to their geographical zone.

RESULTS

RQ1. Which are the Initial Explanations of 4th Graders About Earthquakes and Tsunamis?

Written Explanations

In written explanations we used the categories by Mejías and Morcillo (2006). **Table 1** shows examples of the answers categorized in each one, with a code formed by the ID number, the phenomenon (Earthquake: EQ, Tsunami: T) and the moment (Initial: I, Final: F).

Almost 80% of the children attributed earthquakes to current scientific ideas connected with tectonic plate theory (category 2), at the early moments of formal education, and there was almost 90% attribution when the learning unit was finished. Some examples are "Because the plates collide, it causes an earthquake, and Chile is also next to a plate. The plates collide and form a quake or earthquake" (341, EQ, I) and "The plates move, and the plate moves . . . causing damage" (318, EQ, F). In comparison, 8.4% of the participants related the causes with elements of ancient science which reduced to 1.3% at the end of the learning unit, for instance, "Because of air pressure, a gas comes out and causes the earthquake" (220, EQ, I). About 5% of the students transferred human intentions to the Earth as causes that persisted until the end of the learning unit, as shown in these excerpts "Because the tectonic plates are accommodating because they are uncomfortable" (307, EQ, F), or "Because there is an earthquake because something itches the world" (310, EQ, I).

The initial ideas about tsunamis were more diverse; 52.2% of the students connected tsunamis with elements of tectonic plate theory. For example, "Because there is a tsunami that moves the sea. It is due to the plates moving and making quakes in the sea and generating tsunamis" (208, T, I).

Almost 26% attributed tsunami to ancient science ideas, as shown in these quotations "Due to earthquakes vibrations of the Earth, air pressures accumulate completely" (220, T, I), and "Because the wind creates the waves and there was a lot of wind at the same time . . . a lot of waves came together" (217, T, I). Around 4% held animistic beliefs, and another 4% indicated causes related to astronomy, for instance, "Because when there is a full moon there are high waves . . . to the Earth's rotation (203, T, I), and "Because of the Solar System" (516, T, I). Important changes were found at the end of the learning unit; almost 90% of the students included elements associated with tectonic plate theory, and the category "ancient science" and "animistic ideas" were absent, while nearly 5% kept the causal reasons connected with astronomical factors, such as "Because when there is full moon the high waves can make a tsunami, and people will have to evacuate. There is a lot of movement and high waves are made" (203, T, F).

TABLE 1 | Examples of the students' answers to "Why the phenomenon happens?" by category.

Category	Answer (learning sample in Spanish)	English translation
1	220, EQ, I: Por presión de aire, sale un gas y causa el terremoto 227, EQ, I: Porque se la tragará todo, es un tornado 348, EQ, I: Por los terremotos y temblores, a la energía que hay debajo de la humanidad	220, EQ, I: Because of air pressure, a gas comes out and causes the earthquake 227, EQ, I: Because it will swallow all, it is a tornado 348, EQ, I: Because of earthquakes and quakes, the energy that there is below the humanity
1	220, T, I: Por terremotos vibraciones de la Tierra, presiones de aire que se acumulan completo 207, T, I: Porque pasa por las mareas y los sismos, por las grandes mareas 217, T, I: Porque el viento crea las olas y hubo mucho viento al mismo tiempo ... se juntaron muchas olas	220, T, I: Due to earthquakes vibrations of the Earth, air pressures accumulate completely 207, T, I: Because it goes through the tides and the earthquakes due to the big tides 217, T, I: Because the wind creates the waves and there was a lot of wind at the same time ... a lot of waves came together
2	318, EQ, F: Se mueven las placas, y se mueve ... de la placa provocando daño 341, EQ, I: Porque las placas chocan, provoca un sismo y también Chile está al lado de una placa. Chocan las placas y forma temblor o terremoto	318, EQ, F: The plates move, and the plate moves ... causing damage 341, EQ, I: Because the plates collide, it causes an earthquake, and Chile is also next to a plate. The plates collide and form a quake or earthquake
2	202, T, F: Son por las placas tectónicas, es cuando se crea la subducción, son a la placa de Nazca y Sudamericana 208, T, I: Porque hay un tsunami que mueve el mar. Esto se debe a las placas que se mueven y hacen temblores en el mar y generan los tsunamis 226, T, F: Porque hay un sismo y se forma un tsunami, porque las placas tectónicas se están moviendo en límite convergente	202, T, F: They are due to the tectonic plates; when subduction is created, they are to the Nazca and South American plates 208, T, I: Because there is a tsunami that moves the sea. It is due to the plates moving and making quakes in the sea and generating tsunamis 226, T, F: Because there is an earthquake, and a tsunami is formed because the tectonic plates are moving at a convergent limit
3	303, EQ, F: Por el volcán, volcán	303, EQ, F: Due to the volcano, volcano
4	218, EQ, I: El suelo se mueve porque se significa que está temblando. Yo creo que esto se debe a las personas que botan basura al suelo	218, EQ, I: The ground moves because it means that it is shaking. I think this is due to people throwing garbage on the ground
5	203, EQ, F: Los movimientos fuertes se forman ... yo creo que cuando hacemos cosas malas se mueve la Tierra	203, EQ, F: Strong movements are formed... I believe that when we do bad things, the Earth moves
6	307, EQ, F: Porque las placas tectónicas están acomodándose, porque están incómodas 310, EQ, I: Porque hay un temblor porque al mundo le pica algo 388, EQ, I: Porque las placas tectónicas intentan dividirse	307, EQ, F: Because the tectonic plates are accommodating because they are uncomfortable 310, EQ, I: Because there is an earthquake because something itches the world 388, EQ, I: Because tectonic plates intend to divide
7	203, T, I: Porque cuando hay luna llena hay las altas olas ... la rotación de la Tierra 516, T, I: Por el sistema solar	203, T, I: Because when there is a full moon, there are high waves ... to the Earth's rotation 516, T, I: Because of the solar system
8	505, T, F: Las olas son porque los icebergs se descongelan. En el mar hay grandes olas por el calentamiento global 521, T, I: Porque hay olas por los icebergs	505, T, F: The waves are because the icebergs melt. In the sea, there are big waves due to global warming 521, T, I: There are waves due to the icebergs
9	209, EQ, F: Porque Chile es un lugar sísmico 521, EQ, I: Se mueve el piso por la Tierra y su mecanismo	209, EQ, F: Because Chile is a seismic place 521, EQ, I: The ground moves because of Earth and its mechanism
9	206, T, I: Por la gravedad que empuja las olas, a dos fuerzas distintas	206, T, I: Because gravity pushes the waves at two different forces

[a]The code is formed by ID number, the phenomenon (Earthquake: EQ, Tsunami: T) and the moment (Initial: I, Final: F).

TABLE 2 | Categories of written explanations.

Category	Initial ideas earthquake (%)	Final ideas earthquake (%)	Initial ideas tsunami (%)	Final ideas tsunami (%)
1	8.4	1.3	26.1	0
2	79.5	89.5	52.2	89.5
3	0	1.3	0	0
4	1.2	0	0	0
5	0	1.3	0	0
6	4.8	5.3	4.3	0
7	1.2	0	4.3	5.3
8	1.2	0	0	0
9	3.6	1.3	13.0	5.3

1. Ancient science; 2. Current scientific knowledge of TPT; 3. Volcanic eruption; 4. Anthropogenic actions; 5. Religious beliefs; 6. Animistic; 7. Astronomy; 8. Atmospheric or climatic factors; 9. Other.

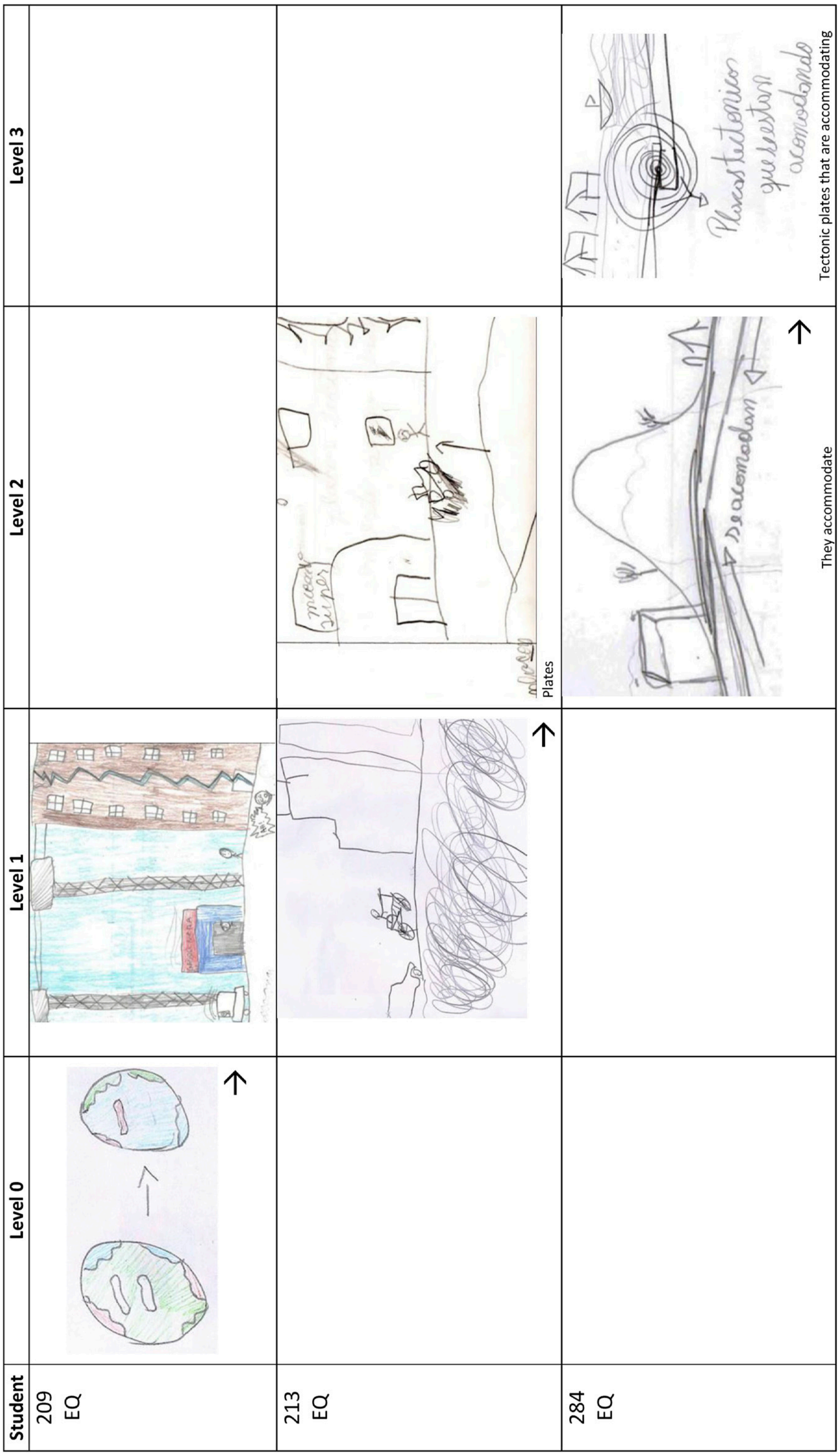

FIGURE 1 | Examples of student's drawing and levels, earthquake (EQ) task. The arrow points to the advance; initial moment → final moment.

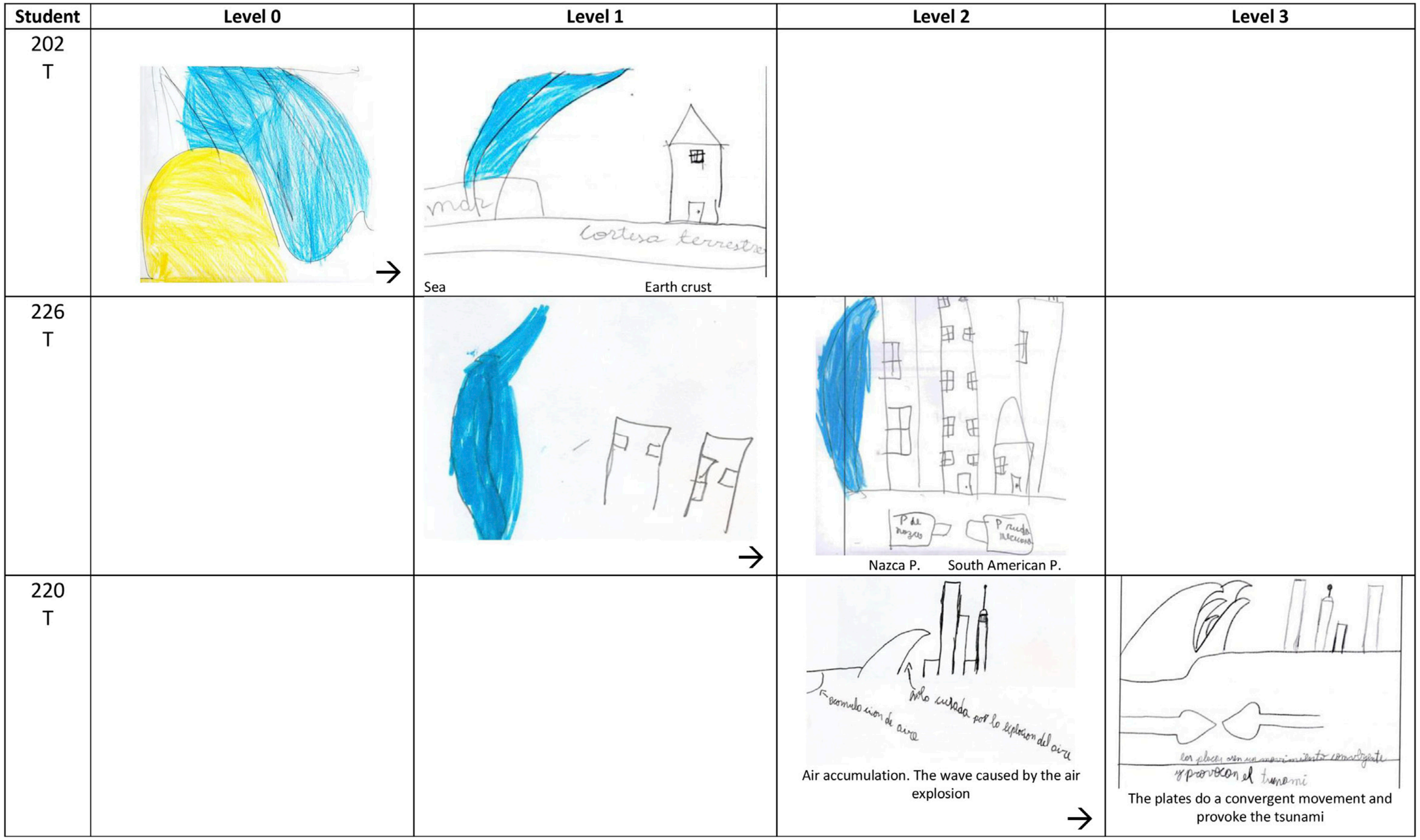

FIGURE 2 | Examples of student's drawing and levels, tsunami (T) task. The arrow points to the advance; initial moment → final moment.

TABLE 3 | Mixed ordinal logit estimates to compare scores before and after a learning unit.

Fixed effects	Drawing task				Writing task			
	Logit	SE	OR	p<	Logit	SE	OR	p<
β_1 Time (post)	1.90	0.58	6.69	**	1.26	0.57	3.53	*
β_2 Zone (capital)	0.04	0.50	1.04	—	1.81	0.55	6.11	***
β_3 Interaction (Time*Zone)	−1.25	0.70	0.29	—	−2.23	0.70	0.11	**
τ_1 Threshold (1,2)	−0.23	0.41	—	—	−1.05	0.45	—	*
τ_2 Threshold (2,3)	1.52	0.46	—	***	1.60	0.49	—	**
τ_3 Threshold (3,4)					3.65	0.61	—	***
Random effects								
Variance ()	0.16	—	—	—	0.73	—	—	—
Model Summary								
Log Likelihood	−144.53	—	—	—	−198.38	—	—	—
observations	140.00	—	—	—	167.00	—	—	—
students	89.00	—	—	—	91.00	—	—	—

Note: logit = unstandardized estimates of the mixed ordinal logit model; SE, standard errors; OR, odds ratio; p < = p *< 0.001 ***,* p *< 0.01 **,* p *< 0.05 *.*

Table 2 presents the categories found percentage wise in the written explanations for both phenomena.

Drawn Explanations

In this task we used a rubric to analyze student's reasoning expressed in explanations (Cabello et al., 2021). The initial students' understanding of why earthquakes and tsunamis occur was not mainly connected with a scientific cause. Some examples are presented in **Figure 1**, categories 0 and 1, which represent the Earth Planet, or consequences of the earthquake such as a broken building (i. e. 209, EQ; 213, EQ). However, almost 41% of them expressed a reason (levels 2 or 3) in earthquake drawings and 33% in the tsunami. These elements were usually represented beneath the ground or sea surface, with arrows, words, or phrases to identify tectonic plate theory elements (i. e., 284, EQ).

After the instructional process, the percentages for levels 2–3 raised to 66% for the earthquakes and 64% for tsunamis. Most participants could represent scientific causal reasoning in the earthquake phenomenon, but an even higher increase was found in the tsunamis. The process of children's reasoning expressed progression from the perceptible and imperceptible to more abstract ways of connecting tectonic plate theory and the phenomena under study. For instance, **Figure 2** shows the advance from level 1 to level 2 (226, T) incorporating the representation of the Nazca and South American plates, and from level 2 to 3 replacing the cause related to "air accumulation" by the plates' movement (220, T).

More sophisticated reasoning regarding the scientific theory underpinning earthquakes and tsunamis was found at the end of the learning unit. Most students connected the causes and consequences with the phenomena, advancing their understanding of hazards in the context of science education.

RQ2. Are there Differences Between the Geographical Zones?

Intending to compare the initial explanations of 4th graders about earthquakes and tsunamis by their geographical zones, we used the Kruskal-Wallis test to assess differences in students' initial scores (Wilcox, 2017). We have 66 students completing the drawing task on earthquakes (coastal = 24, capital = 42), and 86 students completing the writing task on earthquakes (coastal = 26, capital = 60). Regarding tsunamis tasks the sample sizes were not similar and were applied only by the teachers in the coast. Thus, we report scores comparison for the earthquakes drawing and writing tasks. Scores for drawing and writing tasks corresponded to ordinal responses and do not conform to a normal distribution. As such, we deemed it more appropriate to use a parametric test based on rank order to compare initial scores between students.

Among students who completed the drawing tasks (n = 66), we found no evidence of differences in their initial scores corresponding to geographical zones (H = 0.00 df = 1, p = 0.95, Kruskal–Wallis). In contrast, when we compared the students regarding their scores on the writing task (n = 86), we found higher scores among students from the capital zone exposed to the risk of disaster because of earthquakes than students in the coastal zone at-risk of a tsunami (H = 9.02, df = 1, p < 0.001, Kruskal–Wallis).

RQ3. To what extent do 4th Graders' Scientific Reasoning Progress During a Pedagogical Unit?

The analysis of written explanations using Yao and Guo's Scientific Explanation Progression Assessment (SEPA) (2018) showed that 49% of the participants gave answers in the levels 3–4 at the initial moment for earthquakes, while only 26% did it for the tsunami. After the learning module was finished, only 33.7% of the participants explained the levels 3–4 for earthquakes, lower than at the beginning. However, 50% of them attained levels 3–4 for the tsunami phenomenon after the learning module, representing an improvement.

Moreover, to assess the progression of the participant reasoning during a learning unit, we address the main effect between scores and explore if the geographical zone acts to condition these results. We use a mixed ordinal logit model to assess if student scores for the drawing and writing tasks improved after the learning unit. Because scores are ordinal responses, we opt for an ordinal logit model with a cumulative logit link. Indeed, student scores are sample dependents. Each student has a score before and after the learning unit; their scores are not independent observations. Therefore, we recur to a random intercept model to account for score dependencies. We include as "time" a dummy coded variable (0 = before the learning unit; 1 = after the learning unit), and include zone coded in similar fashion (0 = coastal, 1 = capital). Finally, we include an interaction term between these two factors. The present model specification is like an analysis of variance within and between-subject design, adapted for an ordinal dependent variable.

The estimates of these models are logits, or natural log-odds of the proportion of responses above a category and can be interpreted in a linear way (see **Table 3**). Thus, if the time factor results in a positive coefficient, it means students receive higher scores in their task after the learning unit. Similarly, if the zone factor presents positive coefficients, it implies students from the capital received higher scores overall. Finally, if the coefficient β_3 is positive, it means students from the capital reached higher gains than those in the coastal zone. Conversely, if β_3 is negative, then the students from the coastal area have higher gains than their capital peers. All estimates were produced using the R library "ordinal" (Christensen, 2019a; 2019b).

Student scores in the drawing task improved after the learning unit ($\beta_1 = 1.90$, SE = 0.58, $p < 0.01$). Student odds of obtaining higher category scores are about six times larger after the learning unit than before (OR = 6.69). We see no substantial differences regarding zone nor for the interaction between factors.

Student scores in the writing task improved after the learning unit ($\beta_1 = 1.26$, SE = 0.57, $p < 0.05$). Student odds of obtaining higher category scores are about three times larger after the learning unit than before the learning unit (OR = 3.53). In general, students from the capital obtained higher scores than their peers from the coastal area ($\beta_2 = 1.81$, SE = 0.55, $p < 0.001$). The previous results are moderated. Additionally, we assessed if the scores were similar between groups with an interaction term. Students from the coastal zone presented higher gains after the learning unit compared to their peers from the capital ($\beta_3 = --2.23$, SE = 0.70, $p < 0.01$).

DISCUSSION

The current study explored children's understanding of earthquakes and tsunami in risk areas of Chile in a context-based science education learning unit, using drawings and written explanations as a vehicle of children's voice. The fourth graders represented the causes and the origin of the risk situation, expressing their ideas of the earthquakes and tsunami, which was relevant as a first step to advancing their understanding of hazards promoted by science education. Particularly, student scores in the drawing task improved after the learning unit, but we see no substantial differences regarding zone nor for the interaction between factors. Although student scores in the writing task also improved after the learning unit, the participants from the capital obtained higher scores than their peers from the coastal area. Students from the coastal zone showed higher gains in scores after the learning unit in comparison to their peers from the capital.

In this regard, it is known that for disaster risk management, promoting informed actions when events occur is as important as the prior understanding of the causes of the phenomena and the extent to which they can be related to human decisions. It is crucial to empower communities and educate people to prevent the negative impacts of hazards (de Guzman, 2003; Wesely, 2021). Indeed, we agree that the placing of primary education as a core element for raising hazard awareness in the public sphere is possible and urgent (Izadkhah, 2005).

In this study we found most of the participants attributed earthquakes to current scientific ideas connected with tectonic plate theory without formal education, but less than the half of them did it for tsunami. However, with the help of a context-based science education learning unit, the students obtained similar results for both phenomena. Mejías & Morcillo (2006) found that six percent of secondary students related earthquakes to Tectonic Plate Theory (TPT). However, in our study, almost 90% of the children reached this milestone after the learning unit for the earthquakes, which was already high when the learning unit started (80%). This finding might be associated with the context of risk on which the study was conducted, considering that contextual factors matter in understanding phenomena (Bakopoulou et al., 2021). Ancient scientific ideas in other studies were known as myths or religious beliefs (e.g., Tsai, 2001). Nonetheless, in this study, we named them as ancient science, recognizing the role of the history of science in the configuration of knowledge integration and construction of precursor models by children (Ravanis et al., 2013). Moreover, we assume these types of understanding relate to local stories, insights and are culturally relevant. Thus, they are valuable for knowledge integration, complementary towards disaster risk reduction, anchored in local wisdom and mutual enrichment (King & Goff, 2010).

Regarding the students' reasoning, we found no evidence of differences in their initial drawings corresponding to geographical zones, however, we found higher scores among students from the capital zone exposed to the risk of disaster because of earthquakes than students in the coastal zone at-risk of a tsunami. Moreover, we observed a high percentage of children attributed tectonic plates theory as causes of earthquakes and tsunami in the drawing task after the learning unit. More sophisticated reasoning was found at the end of the learning unit. Most children connected the causes and consequences with the phenomena, significantly advancing their understanding of tsunamis as hazards, in context-based science education. The context-based science education for disaster risk reduction has extensive possibilities for research and curriculum design, especially in the cases where children have an animistic understanding of the phenomena. We concur with prior research showing these ideas persist and are difficult to change even with formal instruction (Ross and Shuell, 1993; Mejías & Morcillo, 2006). In the current study, attribution to human intentions to Earth persisted, for example, considering that the Earth is uncomfortable, and it moves with an earthquake. The students who attributed the causes of the phenomena as a punishment or unavoidable hazards might not be empowered to choose safe behavioral alternatives, which is critical for teachers, parents, and policymakers in child-oriented disaster management. Shoji et al. (2020) suggested that these views might impact the children's perception of knowledge but not the perceived response to disasters, making this point exciting for further research.

Some limitations of the study included the different learning sampling sizes that reduced the obtainable quantitative analysis. Additionally, as the study has no control group, it cannot be inferred that the learning unit or the context of risk were causally associated with the results. Indeed, it might be other reasons associated to teaching factors, specific conditions in the classrooms, etc. Although some conditions in this study were quite similar, such as the school socio-economic level or class resources, it is known that the capacity to support innovation can make a difference in the curriculum implementation, especially in developing countries (Rogan & Gryson, 2003). Nonetheless, the descriptive findings of the present work are relevant for raising the explanations of school children about phenomena that might affect their lives, according to their zones, and illustrating the connection between formal science education and aids to risk management which might be accounted for in primary school curriculum design. Here, the mediating role of the curriculum-based material is crucial to targeting high-order thinking skills and not only the recall of knowledge (Cahapay and Ramirez, 2020). We need to consider that many disaster-mitigation and preparedness programs have put disaster topics in the school curriculum because children are supposed to be more receptive than adults (Izadkhah, 2005). However, if we consider children as vectors of hazard education (Finnis et al., 2004), the multiplicative effect of preschool and primary education interventions should be of interest to curriculum developers and policymakers. Indeed, science curriculum can be a cultural tool for student' agency triggering, by giving students a protagonist role in their in-site knowledge construction (Guerrero & Torres-Olave, 2021).

Therefore, policy curriculum design in primary education for mitigating disasters is necessary, considering that learning about the phenomena includes a critical approach to socio-natural disasters and the ways to act with responsibility if they occur. It is particularly relevant in vulnerable zones, due to, for instance, unresponsive education to disasters might increase this vulnerability. We suggest that science educators offer learning opportunities connecting hazards as socio-scientific issues with aspects of understanding the causes and consequences of phenomena. Thus, formal education might enhance a child-centered disaster risk reduction approach (Aitsi-Selmi et al., 2015), promoting student' agency in building personal and collective explanations that can be shared and be valuable for making decisions. Explanations are scientific practices and epistemic tools that support individual and perhaps community resilience. It could mean, for instance, integrating children's ideas as a source of information to construct school evacuation plans/mitigation strategies (e.g., Vásquez et al., 2018) can transfer positive resultant effects from the school to the community (Wachtendorf et al., 2008), informed by a situated knowledge or a socio-cognitive approach as identified in the present study.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not completely available because the qualitative information contain details that could potentially identify the participants. Requests to access should be directed to the corresponding author.

ETHICS STATEMENT

This study involved human participants. The procedures were reviewed and approved by the Comité ético científico de Ciencias Sociales, Artes y Humanidades, Pontificia Universidad Católica de Chile, number 180514006. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Modeling Tephra Fall and Sediment-Water Flows to Assess Their Impacts on a Vulnerable Building Stock in the City of Arequipa, Peru

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Arequipa, Peru's second economic center hosting c. 1,110,000 inhabitants, is the largest South American city exposed to a large variety of natural hazards. At least 200,000 live in areas likely to be affected by hazards from El Misti volcano, located 17 km to the NE. A multidisciplinary project aims to address the impacts of tephra fall and frequent mass flows on the vulnerable building stock and roofs along two ravines that cross the city, enabling decision-makers to undertake retrofitting projects and improve urban risk planning. Two recent eruptions, that is, the 1440–1470 CE Vulcanian event and c. 2070 years BP Plinian eruption, were chosen as references for probable scenarios of potential tephra fall impacts from El Misti on the building roofs. Tephra fall impacts on the city depend on the eruptive style, column height, and patterns of wind directions and velocities over south Peru and roof mechanical resistance. Estimates of potential damage levels and cost range values rely on nine structural types and four classes of vulnerable roofs. Simulation runs of hyperconcentrated flows (HCF) and debris flows (DF), using three depth-averaged flow models (Titan2F, VolcFlow, and Flo-2D) along two drainage basins on the SW flank of El Misti and across Arequipa, examined three scenarios from a database of 39 recent events and other historical lahars. Simulation results showcase the extent toward the city, inundation depths ≤4.6 m, flow velocities ≤9 m/s, and dynamic pressure up to 100 kPa from three different magnitude HCFs and DFs. In both ravines, overbank flows occurred in key urban areas due to channel sinuosity and constrictions near bridges. Potential impacts on habitat stem from ranges of flow dynamic pressure and measurements of construction material. We estimated the monetary loss of buildings according to hyperconcentrated flows and debris flows scenarios to contribute to retrofitting procedure, implementation of defense work, and relocation policy.

Keywords: tephra fall, debris flow, numerical code, building stock, vulnerability, Arequipa

1 INTRODUCTION

About three in five cities worldwide with at least 500,000 inhabitants are vulnerable to cyclones, floods, droughts, earthquakes, landslides, or volcanic eruptions or a combination of those (UN-DESA, 2018). Large cities in Latin America have no exception, as they are most prone to natural disasters. The UN Office for Disaster Risk Reduction reported about 0.50 million victims from natural disasters over the past 20 years in Latin America, and most of them are in large cities, to which environmental issues such as air and water pollution can be added. Examples over the past 20 years are floods that affected almost 4.50 million people in Peru (Alves, 2021). Based on a risk index, which considered the number of people exposed to seismic events per year (2010–2020), Peru ranked the highest with a score of 9.9 and neighboring Chile with 9.8 (Alves, 2021). Recent volcanic eruptions threatened Latin American cities such as Mexico City (Popocateptl volcano), Antigua (Fuego) in Guatemala, Pasto (Galeras) and Manizales (Nevado del Ruiz) in Colombia, Baños (Tungurahua) in Ecuador, and Ubinas (town and volcano) in Peru, to name a few (e.g., Freitas Guimarães et al., 2021).

Peru is among the foremost countries worldwide, with the largest population exposed to natural disasters (Alves, 2021). The deadliest Latin American earthquake since 1900 caused 66,000 fatalities in northern Peru on 31 May 1970, while the second strongest earthquake occurred 200 km West of Arequipa, southern Peru, on 23 June 2001 (Tavera, 2020; Alves, 2021). Although much less frequent, volcanic eruptions have created havoc at the country scale, such as the VEI 6 eruption of Huaynaputina in 1600 CE, the aftermath of which had a global climate impact (Stoffel et al., 2015). Currently, 12 active volcanoes are hazardous for the population living within a distance radius of 30 km around the active vents, while the most active Nevado Sabancaya and Ubinas, among others, are closely monitored by IGP and INGEMMET. Floods, debris flows, and landslides affected almost 4.50 million inhabitants in Peru over the past 20 years (Alves, 2021), and as many as 21,900 floods and landslides have been recorded over the past 10 years according to Civil Protection authorities.

1.1 Scope of the Study and Research Objectives

Arequipa, Peru's second-largest city (1,081,000 inhabitants as per the 2017 national census; INEI, 2018), is one of the fastest-growing regions in the country, at the contact between the Andean highlands and the coast. Arequipa is situated at c. 2,300 masl in a pull-apart basin between the west flank of the Western Cordillera of the Central Andes and the Coastal batholith to the south. This basin was filled by volcanic deposits, mostly Neogene and Pleistocene ignimbrites, covered in part by volcanoclastic deposits that make up the foothills of the Nevado Chachani, El Misti, and Pichu volcanoes. Chachani (6,080 masl) and Pichu (5,600 masl) are extinct volcanic clusters, but El Misti active composite stratocone currently exhibits seismic and fumarolic activity (Aguilar Contreras et al., 2022). Arequipa is the largest South American city exposed to a large variety of natural hazards from El Misti volcano, earthquakes, flash floods, and mass flows. Between 50,000 and 100,000 inhabitants living <1 km from active river or ravine channels are likely to be affected by flash floods and/or lahars, and many more if El Misti volcano, located 17 km NE of the city of Arequipa, produced tephra fall and PDCs. Socio-economic hardships are added to environmental hazards because poor urban development and planning have led to informal settlements and marginal contributions to improving living conditions (INEI, 2018).

The multidisciplinary project "Impacts in the City of Arequipa" aims to address hazards, exposure, and vulnerability of buildings and infrastructure that face frequent flash floods, hyperconcentrated flows (HCFs hereafter), and debris flows (DFs hereafter) along five ravines or quebradas that cross the city. The five ravines are tributaries to Río Chili (inset map, **Figure 1**), whose discharge is artificially controlled for electric supply and water intake. Impacts of potential tephra fallout have also been addressed here so that probabilities of roof collapse in case of eruption may enable stakeholders to undertake retrofitting projects and improve risk management in urban planning.

The research objectives are threefold: 1) to assess the extent of impacts of potential tephra fall on building roofs based on earlier classification of the building stock; 2) to characterize and simulate mass flows, that is, HCFs and DFs in two ravines often affected by floods in the recent past: Quebrada (Qda.) San Lazaro and Qda. Huarangal-Mariano Melgar (Huarangal-MM thereafter), draining the SSW and South slopes of El Misti, respectively (**Figure 1**); and 3) to assess impacts of these flows on the building stock in order to contribute to potential loss assessment.

1.2 Terminology

Flash floods are local floods triggered within 6 h and often within 3 h, generally resulting from heavy rainfall over a catchment (National Weather Service, 2022). Flash floods frequently occur in arid or semi-arid environments where rainfall is concentrated over a short period of time, and the infiltration capacity of the soil is limited so that runoff is triggered shortly after the rainfall onset on relatively steep slopes. Flash floods can occur in cities where construction and pavement made the ground impervious. The environment of the city of Arequipa is propitious to flash floods and mass flows as the result of the semi-arid climate (c. 150 mm a year), the concentration of rainfall as thunderstorms often delivering more rainfall than the average monthly amount. A series of factors favor FFs, HCFs, and DFs across Arequipa (See **Table 1**): (i) short-lasting (3–4 h) and intense rainstorms (26–42 mm/h, from five meteorological stations across the basin of Arequipa over the past 60 years; Fuse and Benites, 2003) typical of a semiarid climate (≤150 mm/year at 2,300 masl); (ii) rapid runoff (30–60 min) in relatively small mountainous catchments (18–40 km^2); (iii) the impervious network of roads and waterproofing of the built-up area that increase runoff; and (iv) the steep, bare slopes of El Misti's foothills carved by ravine channels, which are filled by loose volcanic debris mixed with household and industrial waste

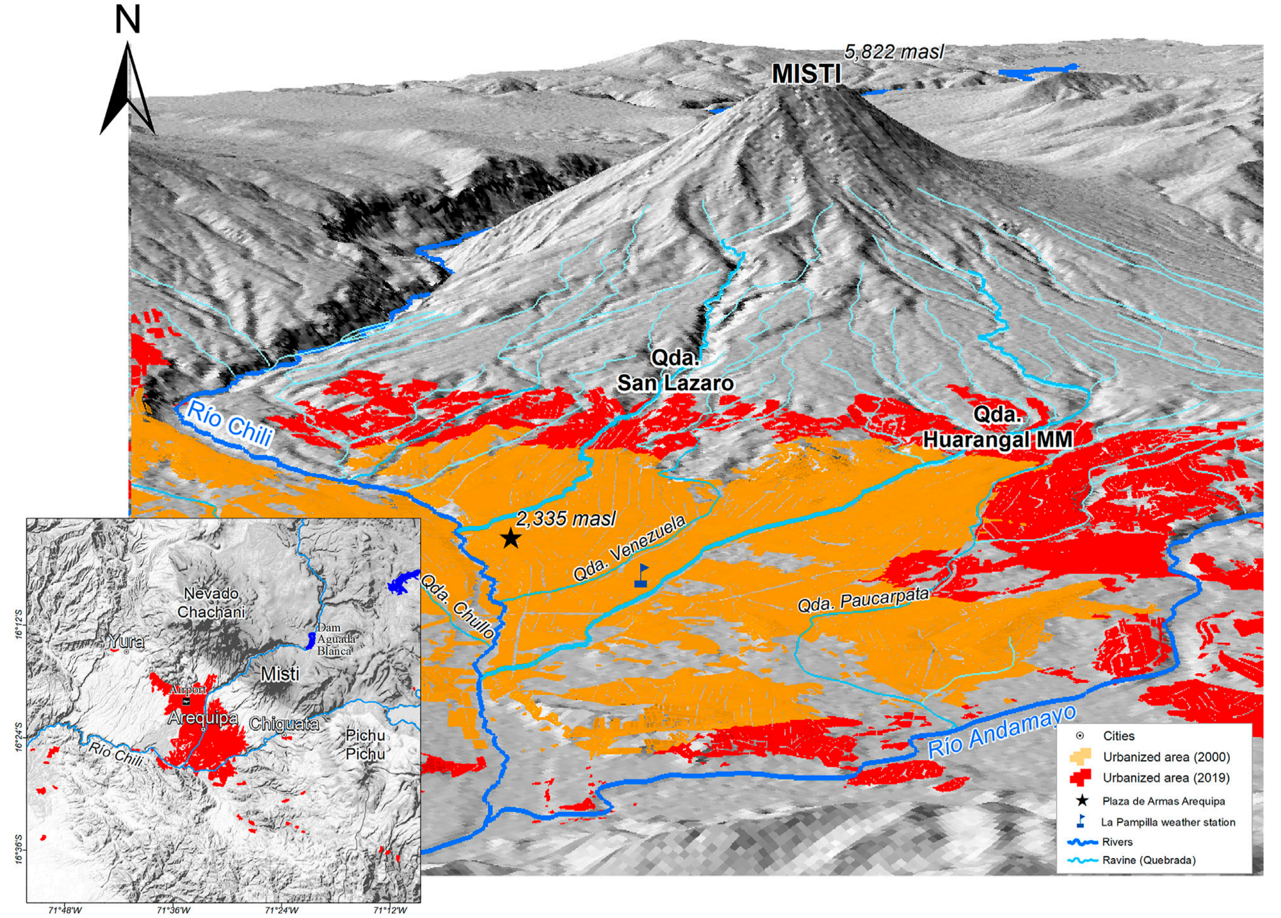

FIGURE 1 | Peripheral growth of the city of Arequipa over the past 20 years. Construction has spread out from the initial oasis and Historic center on the east Río Chili high terrace (1540–1940) onto the volcaniclastic fans SW of El Misti after 1960 and encroached the slopes of the volcano as well as the volcaniclastic apron of Nevado Chachani after 1980. Drainage network including tributaries (locally termed quebradas or torrenteras) to the main artery, Río Chili. Quebrada San Lazaro and Quebrada Huarangal–Mariano Melgar (Huarangal-MM) are the targets of this study. The meteorological station La Pampilla is indicated. Inset map shows the setting of the city of Arequipa, basin, and neighboring volcanoes (active El Misti, dormant Chachani, and extinct Pichu).

(Thouret et al., 2013, 2014; Ettinger et al., 2015; Thouret et al., 2018; Arapa et al., 2019).

Lahars (volcanic debris flows, LHs) and rain-triggered debris flows (DFs) are potentially destructive water-saturated mass flows acting in mountainous regions and areas where steep slopes cut down in loose sediment. These flows can be divided into two categories using sediment concentration, grain-size distribution, and bulk density (Vallance, 2000; Hungr and Jakob, 2005; Manville et al., 2013; Vallance and Iverson, 2015; Thouret et al., 2020):

1. Debris flows (DFs) are mixtures of debris and water with high sediment concentrations that move downslope due to gravity as surging sediment slurries (Vallance, 2000). DFs comprise a solid phase of at least 60 vol% (>80 wt%), thoroughly mixed with water. The solid component includes mostly gravel and boulders with sand, silt, and clay proportions remaining low. A threshold of 3 wt% of silt and clay helps distinguish non-cohesive from cohesive DFs (Scott, 1988; Scott et al., 2005). The density of a DF ranges between 1,800 and 2,400 kg/m^3, twice as much as the muddy water that flows in stream channels during floods (Pierson, 1980).

2. Hyperconcentrated flows (HCFs) are two-phase flows intermediate in sediment concentration between "normal" streamflows and DFs, with densities between 1,300 and 1,800 kg/m^3. HCFs transport between 20 and 60 vol% (40 and 80 wt%) of sediment (Beverage and Culbertson, 1964; Pierson, 2005).

2 METHODS AND DATA ACQUISITION

A combination of methods has involved field surveys and digital data collection, mapping and GNSS surveys for improving the high-spatial-resolution (2–4 m) digital terrain model (DTM), and numerical codes for simulation, as well as assessment of impacts on and potential loss of habitat and bridges.

Surveys at the local scale of neighborhoods (city blocks) along two ravines (Qda. San Lazaro across the north and central parts of

TABLE 1 | Statistical data that result from the database of flow and rainfall events in Arequipa between 1915 and 2020 (see Table). Rn = number of recorded flood/flow events. Sn = number of significant (i.e., causing fatalities and damage) flood/flow events. See **Supplementary Table S1** displays the flow and rainfall events database.

Flow event no.	Average 1915–2020	Flow type %	Monthly occurrence %	Rainfall event Total, intensity, and duration					Rio Chili discharge*** (n = 23)		Fatalities (Rn = 39 Sn = 21)		Affected people (Rn = 21;Sn = 21)		Reported damage (Rn = 39; Sn = 21)				
				Average total rainfall ** n = 14	Average Intensity.	Maximum Intensity	Critical int. threshold	Rainfall duration Average n = 19	Maximum	Average	Total	Average	Total	Average	House		Bridge		Cost US$ million 8 Feb
					Intensity, mm/h (n = 28)										Total	Aver	Total	Aver	
Recorded Rn = 39	2.70	FF 55 HCF 33 DF 12	Jan 33 Feb 54 March 13	76.9 mm	25.30	41.5	24-26	4h19	340 m^3/s	130 m^3/s	N = 39 34	N = 39 0.88	32,656	838	7,610	196	23	0.59	1989 = 0.7 19-20 March
Significant* Sn = 21	4.78	FF 57 HCF 27 DF 16	Jan 22 Feb 64 March 14	79.7 mm	30.10	41.5	28.5-30	4h17	-	-	N = 21 34	N = 21 1.62	32,656	1,556	7,610	363	23	1.10	2001 = 1.8 8 February 2013 = 130

the city and Qda. Huarangal-MM across the NE part of the city, **Figure 1**) allowed us to collect geometrical and technical data (**Supplementary Table S2**) on the building stock using a GIS, data collector, and mapper device (Trimble TC 1000) at the city block or building scale to assess the building stock performance. GIS mapping used high-resolution Pléïades satellite images and Google Earth Pro. A high-spatial-resolution (2–4 m) digital elevation model (DEM) (Oehler et al., 2014) was based on Pléaïdes satellite imagery (2013) using stereophotogrammetry. A digital surface model (DSM) was also produced recently (see Charbonnier et al., 2020 for details) by taking out the obstacles (e.g., bridges) along the ravines in order to avoid excess deposits and subsequent overbank upstream of the bridges. Channel constriction and sinuosity must be accounted for, and its effect must be assessed. GNSS data collection was achieved during two field campaigns throughout the area of the city to tie the DEM to ground control points and two geodetic monuments (Instituto Characato, USGS in Characato, and Instituto Geofísico del Perú in Cayma).

2.1 Assessment of the Potential Impact of Tephra Fall

1. We used probabilistic maps of tephra fall extent and load from El Misti on the city and surrounding areas produced by Sandri et al. (2014). Taking into account past events according to the recorded eruptive styles, the authors ran many simulations using TEPHRA2 (Connor and Connor, 2011) for each type of eruption and volumes of tephra fall between 10^6 and 10^9 m^3. Using a Bayesian event tree and elicitation method, the authors measured a 0.05% tephra-fall probability of occurrence over 1 year for Arequipa in case of Vulcanian, SubPlinian, or Plinian eruption, particularly during the wet season (December–March). Their study provided four maps showing the areal distribution of probabilities of tephra fall with two mass loading thresholds, 100 and 250 kg/m^2, of tephra loads exceedance on roofs for both rainy and dry seasons and two, 10 km and 20 km columna heights (**Figures 6**, **7** in Sandri et al., 2014).

2. We assessed the vulnerability of roofs with respect to tephra load, including two steps: i) field surveys helped us recognize nine types of constructions and roofs based on several criteria collected by means of field surveys across 300 city blocks and ii) classification of about 2,000 buildings was achieved by means of field surveys at the building scale, completed by remote sensing using high-spatial-resolution Pléïades satellite images and drone images (50 and 25 cm pixel, respectively) and Google Street View (**Figures 3A–D**).

2.2 Evaluation of Impacts, Loss, and Cost of Water-Rich Flows on Habitat

1. We elaborated a database of flow events over the period 1915 to 2020 to highlight hydrological input parameters that will be used in numerical simulations (See **Table 1**; **Supplementary Table S1**).

TABLE 2 | Morphometric parameters of the catchments of Qda. San Lazaro and Qda. Huarangal-MM.

Ravine quebrada	Length km	Orientation	Slope %	Gradient	Maximum elevation	Minimum elevation	Watershed area	Watershed perimeter
					Masl	Masl	km^2	km
San Lazaro	14.1	NE-SW	9.2	0.10	3,674	2,371	18.80	30.0
H-MM	20.2	ENE-WSW	5.5	0.05	3,375.5	2,256	26.90	41.10

2. We chose two catchments, namely, the Qda. San Lazaro and the Qda. Huarangal-MM, which initiate >3,300 masl on the SW flank of El Misti volcano, for two reasons: they have been often affected by flash floods and mass flows, and their channels run across a wide range of buildings representing different periods of construction from suburbs to the historic center of Arequipa in the medial and distal reaches, respectively. All ravines, usually dry, become active during the rainy season (December to March) when they convey flash floods and mass flows to Río Chili. **Table 2** displays a few morphometric characteristics of both catchments.

Qda. San Lazaro forms high (3,680 masl) on the SW flank of El Misti volcano and follows a NE-SW direction over a length of 14.1 km with an average slope of c. 8° from its source to its confluence with Río Chili near the Grau Bridge (2,372 masl) (**Figure 2A**). The catchment area is 18.80 km^2. The ravine has incised past lahar and pyroclastic-flow deposits a few tens of meters thick, forming two steep (9%) and widespread (5.50 km × 1.80 km) fans, which have been entirely built over the past 50 years. Qda. San Lazaro has been diverted to the SW, 1 km upstream of the confluence with Río Chili, by the older, eastern fan, which merges down valley with the high terrace supporting the historic center (Thouret et al., 2014). The longitudinal profile of San Lazaro shows three reaches and a gradient of 0.10 (**Figure 2A**). Nine bridges were built over Qda. San Lazaro, the most vulnerable being José Olaya, Parque Selva Alegre, and Ingreso Universidad Católica San Pablo (**Figure 2A**; Thouret et al., 2014).

The source of Qda. Huarangal-MM is located at 3,270 masl on the South flank of El Misti volcano, and the ravine follows an ENE–WSW direction, over a length of 18.9 km with an average slope of 5.3° from its source to the confluence with Río Chili near the suburb Tingo (2,259 masl; **Figure 2B**). Several tributaries join Qda. Huarangal-MM, but the c. 50-m-wide channel narrows down valley near the Geronimo–Paucarpata suburb. As a result, the Huarangal-MM catchment is more extensive than that of San Lazaro (**Figure 2C**; **Table 1**), while its longitudinal profile with a gradient of 0.05 is half as steep as its counterpart (**Figure 2B**). Five amongst ten bridges that cross the ravine are more vulnerable: 8 de Octubre, Tupac Amaru, Jorge Chavez, Santa Rosa, and Gran Unidad Escolar (**Figure 2B**; Thouret et al., 2014).

3. We utilized three numerical codes, Titan2F, VolcFlow, and FLO-2D, to simulate mass flows. Our purpose is to test the abilities of these numerical codes to simulate DF and HCF events and detect their limitations compared with real cases derived from field data or previous simulations described in the literature.

4. We assessed mass-flow impacts on habitat and drew fragility curves involving hydrodynamic and hydrostatic pressure (*via* flow depth) from DF and HCF, resulting from simulations and earlier studies (Mead et al., 2017; see Thouret et al., 2020 for a review of lahar characteristics and impacts). This assessment was completed by *in situ* measurements on home and bridge construction material, both on walls and common construction material, using devices such as sclerometers for hardness and compressive strength, an ultrasonic analyzer for crash resistance, Young's modulus, and surface velocity (Chehade, 2021).

5. Using results from fragility curves for two categories of building wall thickness, we computed loss fractions for the most vulnerable classes A0, A, and B according to the position of buildings adjacent to two ravine channels and the delineated area of simulated dynamic pressure near both ravine channels. From the building loss fractions, we estimated the cost of reconstruction or retrofitting for each vulnerable class of A0, A, and B according to the percentage of building loss fraction in case of DF and HCF.

3 CITY GROWTH AND HAZARDS

The urban area of Arequipa remained relatively compact, mainly on the eastern margin of the Río Chili valley, now the Historic center and UNESCO heritage, from its foundation in 1540 CE until the 1960s (population 86,000) (Gutiérrez, 1992; Thouret et al., 2013; Thouret et al., 2014; Thouret, 2018; Thouret et al., 2018). The population grew rapidly from 81,000 in 1940 to 309,100 inhabitants in 1970, at a rate of c. 6% per year. From 1970 onward, Arequipa has concentrated the largest economic investment in the region, which accelerated people's out-migration from rural areas, also influenced by a succession of droughts on the Altiplano and social unrest in the 1990s. These processes all caused massive out-migration from highlands which contributed to a poorly planned urbanization, poorly designed suburbs, and peripheral low-income settlements that continue to date to the north, northeast, and west of the historic city (Gutiérrez, 1992; Thouret, 2018; Thouret et al., 2018; INDECI, 2019). In 60 years (1970–2020), the built-up area has grown ninefold, from 13 to approximately 115 km^2 (**Figure 1**). As a result, the overall population of Arequipa has increased by more than 330%. Constructions now occupy two-thirds of the basin on both sides of the Río Chili valley and have long encroached upon the lower flanks of El Misti and its western neighbor, Nevado Chachani, as far as 15 km from the historic center, in the form of poorly designed suburbs and "illegal" settlements at the

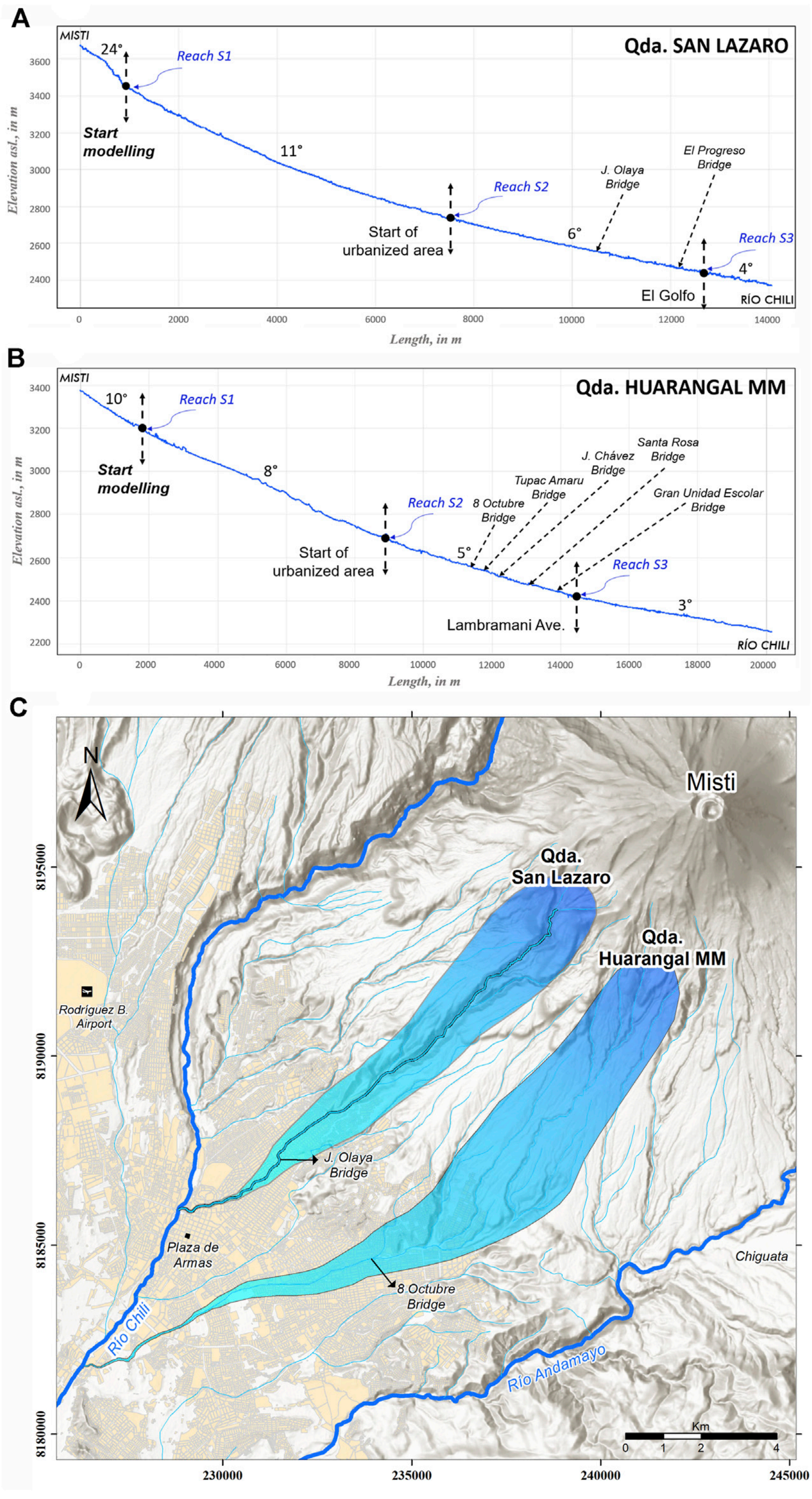

FIGURE 2 | Catchment and longitudinal profiles of the Quebradas (ravines): **(A)** Qda. San Lazaro (SL) and **(B)** Qda. Huarangal-MM. **(C)** Outline and extent of the drainage basins of the two ravines under study. Bridge locations and names are indicated along both ravine profiles. See **Table 1** for morphometric parameters of both catchments.

TABLE 3 | Classification of building and roof types (about 1,500 buidlings in 3,000 city blocks) and estimated vulnerability based on seven criteria in districts adjacent to Qda. San Lazaro and Qda Huarangal-MM (Method after the Plinius Study Centre, *in:* Thouret et al., 2013, 2014 for details). We added estimated cost ranges for each class based on construction or rental cost (per m^2) as of 2018–2019.

Structural typology	Building material, structure and roof	Vulnerability class	Cost range, $US
1	Make-shift housing	A0	≤200
1A	Masonry of lapilli concrete with roof made of metal sheet (1 storey)	A0	250–500
1B	Masonry of ignimbrite without mortar with roof made of metal sheet (1 storey)	A0	250–500
2A	Masonry of terra cotta with roof made of metal sheet (1 storey)	A0	400–700
2B	Masonry of ignimbrite with mortar with roof made of metal sheet (1 storey)	A0	500–800
3A	Masonry of terra cotta with reinforced concrete roof, with structural deficiencies (1–2 storeys)	A	5,000–20,000
3B	Masonry of terra cotta with reinforced concrete roof (1–2 storeys)	A	10,000–30,000
4	Masonry of terra cotta confined in reinforced concrete (RC) frame with RC roof (1–3 storeys)	B	30,000–80,000
5	Masonry of ignimbrite (1,500) with mortar with masonry vaults: historical building (1–2 storeys)	A	100,000–300,000
6A	Masonry of ignimbrite (1,500) modified with RC elements and raisings of type 3 (2–3 storeys)	B	200,000–400,000
6B	Masonry of ignimbrite (1,500) modified with RC elements and raisings of type 8 (2–5 storeys)	B	200,000–400,000
6C	Masonry of ignimbrite (1,900) modified with RC elements (2–3 storeys)	B	200,000–400,000
7	RC buildings without seismic design with RC flat roofs (2–4 storeys)	C	200,000–400,000
8A	New RC buildings with RC pitched roofs (1–2 storeys)	D	200,000–450,000
8B	New RC buildings with RC flat roofs (3–8 storeys)	D	300,000–700,000
8C	Buildings with RC walls and RC flat roofs in the historic center	D	400,000–700,000

periphery. By 1990, urban expansion had engulfed areas that were otherwise bare in 1945, such as the extensive volcanoclastic fans formed by Qda. San Lazaro and Qda. Huarangal-MM. **Figure 1** further displays the city growth area between 2000 and 2019.

Hazard assessments based on the geologic mapping of deposits and previous simulations of volcanic and non-volcanic mass flows, using LaharZ and Titan2D, indicate that the city is highly exposed to natural hazards (Thouret et al., 1995; Thouret et al., 1999; Thouret et al., 2001; Delaite et al., 2005; Mariño et al., 2007; Vargas Franco et al., 2010; Martelli 2011; Cobeñas et al., 2012; Cobeñas et al., 2014; Thouret, 2018). The most threatening hazards for Arequipa, set in impact and frequency order, are the destructive (Mw ≥ 8) earthquakes with a 10% probability exceedance in 50 years (Aguilar et al., 2017); 2) the potentially destructive (VEI 2–4) eruptions of the active El Misti with an estimated recurrence of 500–2,000 years (Thouret et al., 2001); and 3) the low-to-moderate magnitude ($0.1–1 \times 10^6$ m^3) and high-frequency (2.7 years on average) flash floods and mass flows (**Table 1**; **Supplementary Table S1**).

3.1 Tephra-Fall Hazard

Potential volcanic hazards from the active El Misti are acute, as the recorded eruptive activity exhibited a variety of styles and deposits (Thouret et al., 2001; Harpel et al., 2011; Charbonnier et al., 2020). Among the volcanic hazards (**Supplementary Figure S1**), we focus on tephra fallout, while modeling of PDCs has been the target of recent work (Charbonnier et al., 2020). Tephra fall is considered the most common hazard from volcanic activity. It has rarely caused human life loss, but the high mobility of small particles is responsible for health problems and has economic impacts in cities around active volcanoes. Globally, the impacts of tephra fall include building roof collapse, damage to aircraft, disruption of lifelines, and health and environmental effects. Tephra fall from El Misti occurred in the mid-15th century in Arequipa and fine ash from Nevado Sabancaya in 2016. However, explosive activity over the past 50,000 years has shown a succession of Vulcanian to Plinian eruptions and a frequency of about 500 years for VEI 2 events and 2,000–5,000 years for VEI 3-4 events (Thouret et al., 2001; Sandri et al., 2014).

Holocene and historical Misti's activity has encompassed a range of eruptions with VEI 2-4 magnitudes. Two recent eruptions (i.e., the 1440–1470 CE Vulcanian event and the ca. 2070-year BP Plinian eruption) are working references for probable scenarios (e.g., Sandri et al., 2014). Tephra-fall deposits at least 10 cm thick were emplaced by the mid-15th-century event (Chávez, 1992; Thouret et al., 2001), while 2070-year BP pumice-fall deposits exceeding 50 cm in thickness have been observed across the city area (Cobeñas et al., 2012; Cobeñas et al., 2014; Harpel et al., 2011; Harpel et al., 2013). Dispersal of tephra fallout toward the city depends principally on the eruptive style, column height, and patterns of wind directions and velocities over southern Peru.

3.2 Floods and Mass-Flow Hazards

Mass flows including DFs and HCFs threaten the city area, to which flash floods (FF) are added in the semi-arid environment of southern Peru. We selected 39 FFs and mass-flow events over the period 1915–2020 from reports, newspapers, and previous studies (e.g., Fernandez-Davila and Benites Montufar, 2003) that we completed with INDECI (National Institute of Civil Defense) reports (2019) on disasters (**Table 1**; **Supplementary Table S1**). As a result, FFs and lahars (HCFs or DFs) occur every 2.7 years on

TABLE 4 | Building roof types and vulnerability classes based on eight criteria. **Barrio de invasion:* "illegal" settlement, settlement without basic needs given to new migrants for a small amount of money or with the purpose to obtain electoral support or political influence. ***Size or area:* small (<100 m^2), medium size (100–300 m^3), large size (300–1,000 m^2), very large size (>1,000 m^2).

BUILDING ROOF TYPE 9 categories	**Small house or modern pavilion 1**	**Regular quality house, suburb 2**	**Recent, high-income house 3**	**Regular- to poor-income house, suburb & "*barrio de invasion*"* 4**	**School or administration building 5**	**High-rise, modern building 6**	**Composite, low- income business, shelter, shabby house 7**	**Historic monuments, old, maintained buildings 8**	**Sport or leisure facility areas, open market, gas station 9**
Roof slope	Flat or single pitched	Flat	Pitched	Flat	Flat	Flat	Flat or low angle	Rounded Vaulted mansonry	n.a. (not applicable)
Construction material & cover	Cement slab with concrete beams or tiles cover	Metal sheet (zinc, corruga-ted iron)	Concrete slab with RC beam; Tiles	Light material (tent, plastic or wood) on cement slab	Brick or cement slab, with RC beams	RC slab	Heterogeneous (cement, wood, light) above weak ceiling	Ignimbrite or concrete with beams	Open or tent (linen or plastic)
Building use	Habitat (house)	Industrial, business, supermarket habitat	Modern or decorated house	House or shelter; Un-finished (partly open sky)	Several storey-house or building	Residential and/or offices	Shed, garage or business; unfinished (open sky)	Church Convent, Government	Sport
Roof size (area) **	< 100 m^2	100 to 200 m^2	200–300 m^2	<100 m^2 and 100–200 m^2	300–500 m^2	500–1,000 m^2	≤100 m^2	300–600 m^2	500–>1,000 m^2
Number of storeys	1	1	2 or 3	1 or 2	≥2	>3	1 or 2	High	n.a.
Maintenance	Good	Regular to poor	Very good	Regular to poor	Regular	Good	Poor conditions	Sturdy	Regular
Period of construction	10 to 30 years ago	20th century	10 to 20 years	20th century or recent 'invasion'	20 to 50 years	10–20 years	20th century	16–19th century	10 to 40 years
Roof,resistance Collapse threshold (kPa)	Good (4–6)	Poor (1.5–3)	High (5–10)	Poor or structurally deficient (1–3)	Good (5–10)	High (7–12)	Poor or structurally deficient (≤2)	High (7–10)	Poor or n.a. (1–2)
Roof vulnera-bility class	C	**B**	D	**A**	C	D	**A**	D	**A**

average and can be lethal and destructive every 5 years on average (**Table 1**; Nagata, 1999; Thouret et al., 2013; Thouret et al., 2014; Xue, 2016). The disrupting flows affected about 33,000 inhabitants and damaged more than 7,600 buildings over the past 105 years (**Supplementary Table S1**; Regional de Arequipa, 2014; INDECI, 2019). One of the destructive and lethal events occurred on 8 February 2013 when heavy rainfall (124.5 mm during 3 h) triggered an HCF and extensive flood along the Qda. Venezuela, affecting 280 buildings and 23 bridges in the city (Ettinger et al., 2015).

4 BUILDING STOCK AND ROOF CLASSIFICATION

To assess potential damage, we mapped and ranked the structural types and vulnerable classes of the building stock across 300 city blocks, including about 1,500 buildings. Two additional campaigns in 2018 and 2019 enabled us to complete the structural classification at the house scale along both quebradas (**Supplementary Figure S2**) (Thouret et al., 2013; Thouret et al., 2014). Field surveys collected data such as usage, quality of the construction material, surface area, structural support, openings, and roof types for the building performance (**Table 3**; **Supplementary Table S2**), completed through remote sensing using two high-spatial-resolution Pléaïdes satellite images as of 2013 (Thouret et al., 2014). Prieto et al. (2018) quantified the relationship between hazard intensity and building performance. The structural characteristics bearing on the resistance of buildings to mass-flow hazards include weight-to-breadth ratio, structural yield and/or ultimate lateral capacity, and associated model parameters (α_1 and λ). In order to compute these ultimate parameters for building resistance, a handful of variables need to be collected in the field and from imagery: building height, length and weight/breadth, inter-story height, thickness and density of walls, slab weight over the floor area ratio, the vertical axial stress on the base of walls, and masonry shear resistance. In addition to these structural elements most pertinent for the structural types to be

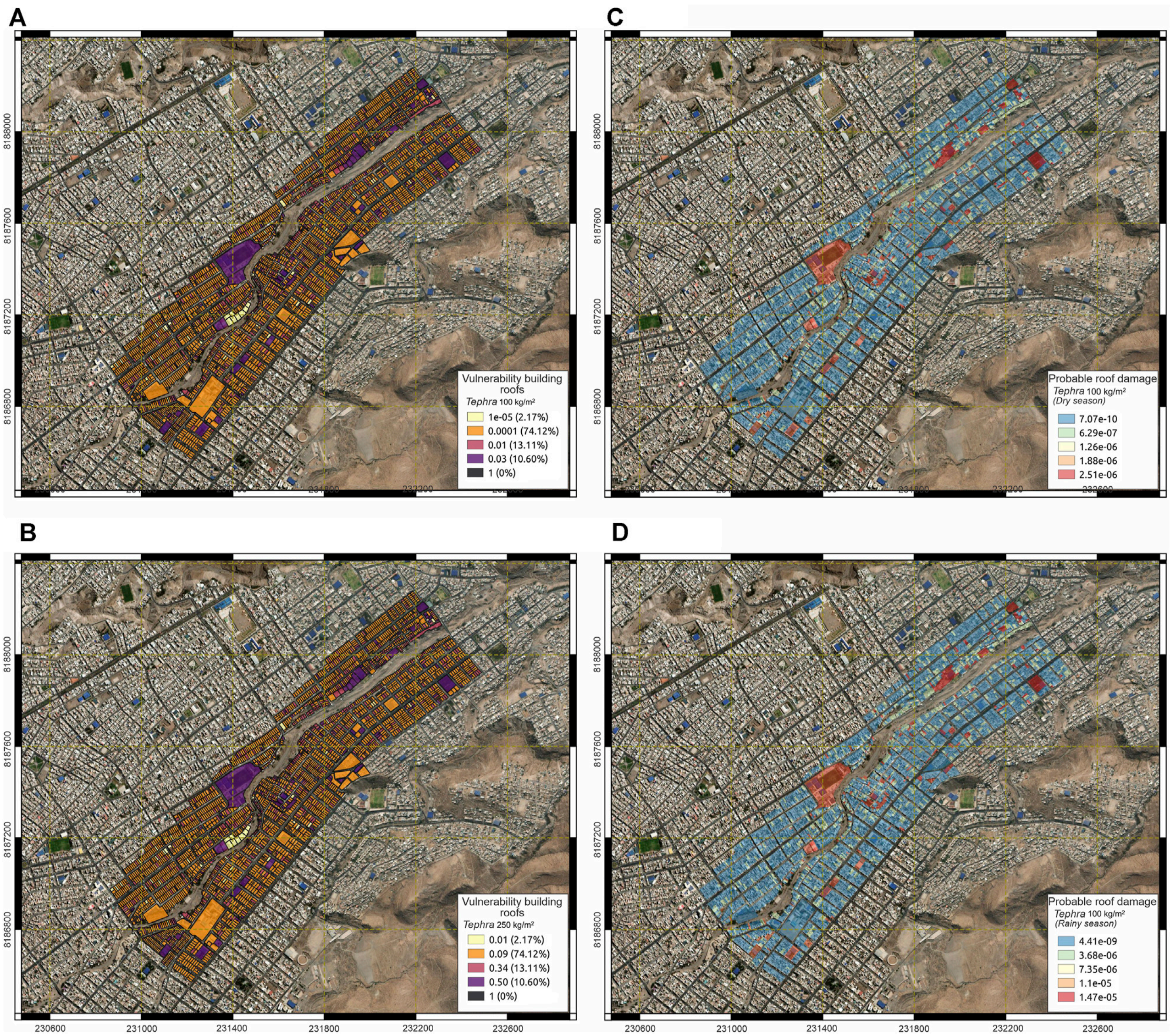

FIGURE 3 | Areal distribution and vulnerability index of roof classes along the medial reach of Qda. San Lazaro according to **(A)** Tephra mass loading of 100 kg/m^2 and **(B)** Tephra mass loading of 250 kg/m^2. Evaluation of roof damage probabilities in the medial reach of Qda. San Lazaro for **(C)** Tephra mass loading of 100 kg/m^2 and **(D)** Tephra mass loading of 250 kg/m^2.

identified, we add the edifice shape, presence or lack of master design, and resistance of the construction material.

Eight structural types of buildings were classified based on structural support, prevailing construction material (brick, masonry, concrete, ignimbrite, or adobe), openings, and roof type, among others (Thouret et al., 2014). A series of 15 architectural and structural characteristics helped determine the least to the most vulnerable building classes (**Supplementary Table S2**). The structural types have been summarized and ranked according to four vulnerability classes A0, A, B, and C (**Table 3**; **Supplementary Figures S2, 3**). Distinct vulnerability classes were supported by an inventory of heavy, significant, and slight damage levels observed on buildings in the wake of the 2013 disastrous HCF along Quebrada Venezuela (Ettinger et al., 2015).

Typical building materials in Arequipa differ from the rest of Peru and usage helped us rank them. 1) Bricks and masonry that have been present in Peru since 1916 represent >62% of the construction materials due to the prevalence of clay soils and new technologies. Industrial bricks exhibit homogenous dimensions and higher resistance to compression than artisanal bricks. 2) The "sillar," an unwelded white ignimbrite, represents 23% of construction materials (INEI, 2018); the use of sillar increased after the 1582 earthquake that left the city of Arequipa in ruins (Silgado, 1978). The sillar now used for the construction of monuments and hotel or residence facades stems from

TABLE 5 | Structural description and vulnerable classes of roofs with estimated range of construction cost. Vulnerability index and damage value. Inset graphics represent tephra load vs thickness for two tephra-fall deposits taken as probable eruptive scenarios of El Misti, i.e., the mid-15th Century vulcanian event (maximum 10 cm thickness over the city area) and the c. 2070 yr BP Plinian eruption (maximum 50 cm thickness over the city area). Damage value after Blong et al (2017): 0 No damage; 1 Light damage (gutters), cleanup required; 2 Moderate damage, bending or excessive damage to as much as half roof sheeting and/or purlins, Interior requires cleaning, repainting, and/or overhaul of electrical systems; 3 Heavy damage to roof structure and some damage to walls; at least one wall damaged. Collapse of part of ceiling.

Roof Type	Vulnerability class (after Blong)	Description after Blong et al. (2017), modified and adapted to the Arequipa case (see Table for details)	Surface area (10^3 m^2)	Area proportion %	Estimated range of construction cost, US$
1	C	Flat or single pitched, cement on timber rafters/trusses, in good condition. Tiles on timber trusses, in average or good condition	606.814	66.75	1000–2000
2	B	Long span, flat roofs with metal sheet or fibre reinforced concrete sheets, in average condition	119.220	13.10	≤200
3	D	Pitched roofs on timber rafters/trusses, in average or good condition, or concrete slab with RC beams	10.423	1.15	2000–4000
4	A	Flart roof, weak timber boards on timber rafters/trusses; Light material roof on timber rafters/trusses, in old or poor conditions	13.556	1.50	100–200
5	C	Flat roof, brick or cement slab on timber rafters/trusses, in good condition; fibre reinforced in average or good condition	66.972	7.35	2500–5000
6	D	Flat rooof, RC slab on strong timber rafters/trusses in good condition	8.511	0.95	3000–7000
7	A	Flat or low-angle roof, heterogeneous or light material on weak timber boards, in poor condition, rafters/trusses; Metal sheet roof on timber rafters/trusses, in old or poor conditions	17.814	1.95	100–200
8	D	Vaulted mansonry roofs, concrete or ignimbrite masonry with strong timber rafters/trusses, in good condition	0.769	0.10	2000–5000
9	A	Open area without roof or light material (tent, pastic), no timber or weak timber boards, in average or poor condition	65.023	7.15	≤200

Building Class	Vulnerability to tephra mass load 100 kg/m^2	Vulnerability Index	Vulnerability to tephra mass load 250 kg/m^3	Vulnerability Index	Central damage value
A	0.03	V1	0.50	V3	0.4
B	0.01	V0	0.34	V2	0.1
C	0.00010	V0	0.09	V1	0.03
D	0.00001	V0	0.01	V0	0

quarries along the Añashuayco ravine west of Arequipa Airport, where the Arequipa Airport Ignimbrite is mined (Paquereau-Lebti et al., 2006; Paquereau-Lebti et al., 2008). More fragile construction materials such as wood and corrugated iron represent 10%, according to the information collected in the 2017 census. Adobe is much less common at ≤5%, compared to ≥25% for the country (INEI, 2018).

4.1 Structural Types of Roofs and Potential Impacts of Tephra Fall

Structural classification of nine roof types (**Table 4**), based on Blong et al. (2017) classification and field surveys, encompasses mostly habitat buildings and administrative, educational and religious edifices, historic monuments, and sport facilities. Types 1, 2, 3, 4, and 6 are houses and residential buildings, while types 5, 7, 8, and 9 correspond to commerce and other edifices (**Supplementary Table S4**; **Supplementary Figure S3**). We defined five types of residential habitats ranging from houses with poor quality of construction material (e.g., type 4) to residential, 2 + story buildings for which design, structure, and material offer better resistance to load and impacts. Poor quality and vulnerable houses either have roofs made up of light material (plastic, wood, zinc, or a combination of those) or are often unfinished constructions without a roof. Type 2 average quality houses and commerce or industrial buildings have metal roofs and better-quality materials. Types 1 and 3 are high-quality and resistant buildings, while type 3 edifices show a better design and roof resistance due to pitch and reinforced concrete. Type 6 includes high-rise edifices with reinforced concrete, and potential impacts from tephra fallout have been estimated in terms of probabilities. The impacts would be more important during the rainy season when wind patterns would disperse more tephra toward the city area (**Figures 6**, **7**inSandri et al., 2014). We assessed the extent of roof damage by comparing the tephra load (in particular 250 kg/m^2) with the least resistant buildings and roofs that belong to vulnerability classes A0 and A. The latter classes prevail along the upper and middle reaches of both quebradas (**Supplementary Figure S2**).

We refer to Sandri et al. (2014) for the probability maps of tephra fall with 10 or 20 km high eruption column heights, wind patterns, and velocities during two dry and wet seasons in southern Peru and for two hazard metrics (tephra loads of 100 and 250 kg/m^2). We evaluated the structural performance and

TABLE 6 | Estimate of discharges and return periods of mass flows in Quebradas compared with discharges and return periods of Río Chili floods obtained using a Gumbel distribution.

Recurrence interval (years)	2	5	10	50	100
Discharge m^3/s Quebradas	19	45	85	124	160
Discharge m^3/s Río Chili	62	110	142	238	340

susceptibility of roof collapse across built areas along both banks of Qda. San Lazaro and Qda. Huarangal-MM. Each building roof was classified based on seven criteria, including quality of the construction material, usage, and surface area. We obtained nine types of roofs mapped in the Q-GIS software.

4.2 Vulnerability Index of Roofs and Probable Damage

The nine roof types have been converted into four vulnerability classes (Blong et al., 2017) according to the mechanical resistance of the material and based on two hazard metrics 100 and 250 kg/m^2. These tephra loads, in turn, yield pressures of 1–2 kPa and forces of 1,000 and 2,500 N/m^2 (inset graphics, **Table 5**). A substantial proportion (38% in area) of regular-quality roofs may not withstand 250 kg/m^2 or 2.5 kN/m^2, and almost all low-quality roofs (11%) may suffer structural damage or collapse if the tephra load reaches 100 kg/m^2 or 1 kN/m^2. Particular attention was paid to light and heterogeneous material covering low-quality houses, ranked as "hybrid" roofs, which can be affected by minor tephra loads ≤100 kg/m^2. Flat roofs or upper ceilings without proper cover may be more vulnerable than pitched roofs, a category that represents 3%-4% (in area) only of the surveyed buildings located in high-income neighborhoods only. Both values of hazard metrics may increase in case of rainfall concomitant with tephra fall because the probability of ashfall toward the city increases during the rainy season (Sandri et al., 2014). Both values of forces (1–2.5 kN/m^2) are 2.5–6 times lower than forces exerted by tephra thickness between 20 and 50 cm in case of Plinian tephra fall (inset graphics, **Table 5**), to be compared to the 50-cm-thick 2070 BP pumice-fall deposit observed in the north and NW areas of the city.

The vulnerable roof classes rely on structural description and mechanical resistance (**Table 4**), which has led to impacts according to damage level in case of tephra fall exceeding the tephra loads and forces defined above (**Figures 3C,D**). From maps of vulnerable roofs and vulnerability index (**Figures 3A,B**; **Table 5**), we estimate three damage levels in case of the higher hazard metrics (load of 250 kg/m^2 defined above): 1) heavy/severe (i.e., roof collapse and burnt timber, failure of trusses and supporting structure, severe to moderate damage to rest of the edifice) for roof types 4, 7, and 9 (c. 11% in area); 2) significant damage to the roof structure and some damage to walls, at least one wall damaged/misaligned, collapse of part of ceiling for roof type 2 (c. 13%); and 3) slight (bending, damage to roofs overhangs and ceilings without roof, required cleaning, repainting or material overhaul) for roof types 1 and 5 (c. 14%). If the tephra load exceeded 250 kg/m^2 and reached about 6 kN/m^2, which would be the case with a 50-cm-thick tephra fall comparable to the c. 2070 BP Plinian pumice-fall (i.e., between 5 and 6 kPa), the aforementioned roof types (categories A, B, and C; **Table 4**) would all experience collapse, while moderate-to-severe damage would affect the rest of edifices. If we consider the probability of roof collapse triggered by a combination of tephra load (250 kg/m^2) and rainfall, the proportion will increase to the majority of roof categories beyond classes A, B, and C, except for the RC (reinforced concrete) and pitched types of roofs, category D.

We estimated the cost of roof construction in case of damage due to tephra mass loading (inset graphics, **Table 5**), considering at least 425 building roofs along the medial reach of Qda. San Lazaro together with the proportion and estimated cost range of each roof type (**Table 5**). Severe damage of 75% of low-quality roof types 4, 7, and 9 would amount to a range of 18,000–20,000 US$. Significant damage of 50% of regular-quality roof type 2 would reach 6,000–8,000 US$, while slight damage of 25% of average-quality roof types 1 and 5 would translate into a cost range of 75,000–80,000 US$.

5 RECORD OF SEDIMENT-WATER FLOWS

The analysis of a 105-year database (1915–2020) in Arequipa helped describe the key characteristics of rainfall and flow events (**Table 1**; **Supplementary Table S1**).

5.1 Characteristics and Occurrence of Flash Flood and Mass-Flow Events

Flash floods were the most frequent events (55%), while HCF represented 33% and DF only 12% of the total events. Because solid concentration was not measured *in situ*, DFs with at least 40% vol. solid concentration may actually be more frequent. All flow events occur during the rainy, austral summer, with the majority (54%) in February, 33% in January, and 13% in March. Over 105 years, one event occurred every 2.70 years on average. A significant flow event (i.e., with >1 fatality and damaged buildings and/or bridges) occurred every 5 years on average.

Rainfall Events Triggering Flows/Floods

Considering the recorded rainfall intensity for 28 recorded events that triggered flows lasting 1.5–3 h, the average rainfall intensity is 25.30 mm/h. Maximum intensity rainfall reached c. 41 mm/h, according to Fuse and Benites (2003). We estimate the critical rainfall intensity to be in the range of 25–26.5 mm/h, increasing to 28–30 mm/h for more destructive and lethal flow events. In fact, the critical threshold depends on the total rainfall during 24 h or preceding days and the duration of the triggering rainfall (see below). As many as 21 events spanned 2 to 5 days of intermittent rainfall. The average rainfall intensity was 31.1 mm/h, and the maximum was 41.5 mm/h during the 8 February 2013 flow. Most flows were triggered just before or during the maximum rainfall intensity.

The duration of the rainfall events ranges between 2 and 8 h. The average was 4 h and 19 min for 19 rainfall events that

TABLE 7 | Comparison of input parameters used in mass-flow numerical simulations (from the literature) compared to our simulations using Titan2F, VolcFlow and FLO-2D codes.

Input Parameters	Unit	Model used	Publications[a]		Our simulations	
			HCF	DF	HCF	DF
Volume	$\times 10^5$ m^3	VF, T2F, Fl2D	1.0–6.0	1.0–6.0	1.5–5.0	1.5–5.0
Solid concentration	%vol.	T2F, Fl2D	20–50	50–80	30–40	60–70
Yield strength	Pa	VF, Fl2D	<50	<400	1–20	50–100
Bulk density	kg/m^3	VF	1,300–1,800	1,800–2,300	1,300–1,600	1,900–2,200
Viscosity	Pa.s	VF	0.1–10	<50	0.01–1	10–50
Internal friction	degree	T2F	20–35	20–35	20–33	20–33
Basal friction	degree	T2F	10–20	10–20	10–18	10–18
Manning's coefficient		Fl2D	0.01–0.1	0.01–0.1	0.03–0.08	0.03–0.08
Froude number		Fl2D	<1 (subcritical flows)	<1 (subcritical flows)	0.9	0.9
Laminar flow resistance		Fl2D	24–50,000	24–50,000	400	400
Peak discharge	m^3/s	Fl2D	10–500	10–500	20–400	20–400
Volumetric discharge	m^3/s	VF, T2F, Fl2D	20–1000	20–1000	25–300	25–300
Duration	s	VF, T2F, Fl2D	14,400	14,400	7,200–10,800	7,200–10,800

VF = Volcflow, T2F = Titan2F, Fl2D =FLO-2D.

[a]*Woohliser, 1975; Pierson and Costa, 1987; Phillips and Davies, 1991; Rickenmann, 1991; Major and Pierson, 1992; O'Brien et al., 1993; Iverson et al., 2010; Martelli, 2011; Manville, 2013; Charbonnier et al., 2017; Thouret et al., 2020 (references therein).*

triggered flows. The total precipitation over 24 h on average was 76.9 mm for 14 recorded rainfall events with a minimum of 30.5 and a maximum of 190.2 mm. On 8 February 2013, the meteorological station La Pampilla (monitored by SENAMHI, 2013) registered 124 mm of rain during 3 h, which was a c. 100-year return period rainfall event.

5.2 Mass-Flow Characteristics

Ettinger et al. (2015) reported some characteristics of the 8 February 2013 HCF. Total volume of the flow ranged between 50,000 and 100,000 m^3. Peak flow discharge increased from 124 m^3/s in the upstream reach to 425 m^3/s in the middle reach, and the average discharge was seven times that of average discharge (19,50 m^3/s) of streamflows (maximum 43 m^3/s in San Lazaro and 69 m^3/s in Huarangal-MM; Fuse and Benites, 2003) occurring in the rainy season. Velocity ranged between 5.9 and 10.9 m/s and flow depth between 3 and 6 m. The return period of discharges in Quebradas using the Gumbel distribution was compared to the case study of Río Chili (Martelli, 2011) and estimated on the basis of discharges reported from the 2013 event (**Table 6**).

Reported Fatalities and Damage Caused by Significant Flow Events

Twenty-one flood/flow events induced victims and significant damage that was measured *in situ* or estimated afterward. For example, extensive damage was reported for two events in 1989 and 2013; the 8 February 2013 flow killed five persons and affected 22,970 people. About 4,540 homes were affected and 150 were destroyed, while 10 bridges were badly damaged (INDECI, 2019).

Fatalities totaled 34 persons over 105 years, yielding 0.88 fatalities on average per flow event, but we counted as many as 32,656 affected (displaced, homeless, or injured) people. On average, 838 people were affected per flow event, a figure doubling in case of destructive or lethal events. The total number of affected buildings is estimated to be 7,610, that is, 196 per flow event or 363 per destructive flow event. As many as 23 bridges were reported to have been damaged by flow events over the period 1915–2020.

6 COMPLEX MASS-FLOW RHEOLOGY AND MODELING

The sediment-water flows, including HCFs and DFs, exhibit a complex flow behavior determined by physical and rheological properties (Pierson and Costa, 1987; Phillips and Davies, 1991; Rickenmann, 1991; Major and Pierson, 1992; Iverson, 1997; Rickenmann, 1999; Lavigne and Thouret, 2003; Iverson, 2014; Iverson et al., 2011; Manville et al., 2013). The complexity and variability of HCF- or DF-properties during their propagation make them difficult to characterize and thus define a physics-based model. According to Takahashi (2014), some models consider a single-phase continuum fluid or two-phase continuous fluid (mixture theory), such as the Newtonian fluid, Coulomb-viscous fluid, Bingham fluid, Herschel–Bulkley fluid, and dilatant fluid (George and Iverson, 2014). Furthermore, the dynamic behavior of lahars/DFs has led to a variety of modeling approaches, ranging from simple empirical models to physics-based models (Manville et al., 2013). DFs exhibit a behavior that may be compatible with the Bingham viscoplastic fluid, the viscosity of which is independent of shear rate (Major and Pierson, 1992; Manville et al., 2013), which can reach up to 1.5 order of magnitude greater than the viscosity of HCFs. Viscosity strongly depends on sediment concentration and the amount of silt and clay (Bardou et al., 2007). DFs possess a yield strength that can vary from tens to hundreds of Pa, which must be lower than the shear stresses, and alike viscosity is also very sensitive to the sediment concentration (Phillips and Davies,

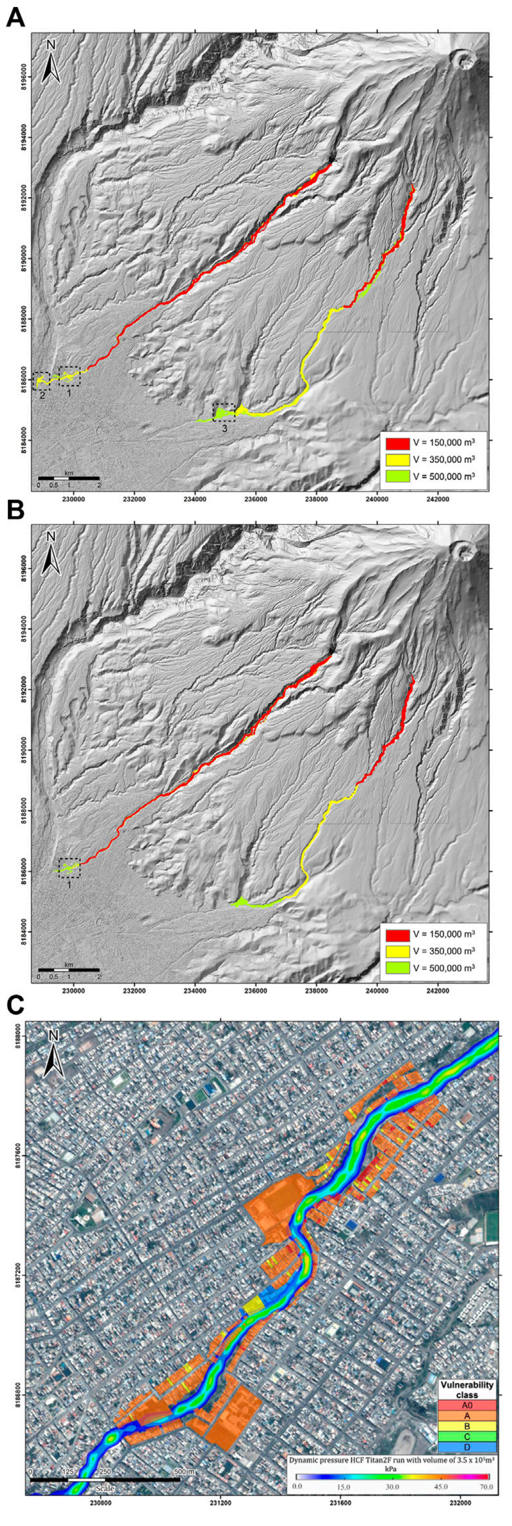

FIGURE 4 | (A) Titan2F-simulated HCFs with a range of three volumes (1.5, 3.5, and 5 × 10^5 m^3) in Qda. San Lazaro and Qda. Huarangal-MM. Rectangle #1 shows the overbank near the Progreso bridge down valley San Lazaro. Rectangle #2 shows damming by a moderate volume DF and subsequent runup at the confluence of Río Chili. Rectangle #3 indicates the overbank area in the Geronimo–Paucarpata suburb in Huarangal-MM, similar *(Continued)*

FIGURE 4 | to the actual overbank area inundated in 2011. **(B)** Titan2F-simulated DFs with a range of three volumes (2.5, 3.5, and 5 × 10^5 m^3) in Qda. San Lazaro and Qda. Huarangal-MM. **(C)** Distribution of HCF dynamic pressure (using Titan2F) in the middle reach of Qda. San Lazaro with a volume of 3.5 × 10^5 m^3.

1991; Major and Pierson, 1992; Iverson, 2005). When the complex behavior of DFs or lahars needs to be described, the presence and interactions of the two (solid and fluid) phases cannot be neglected (Iverson et al., 2010; Iverson, 2014).

HCFs typically possess a small but still measurable static yield strength of a few tens Pa, which can increase as it is strongly influenced by the amount of fine material (Rickenmann, 1991; Pierson, 2005). The viscosity is between 10^2 and 10^4 times greater than the viscosity of water, which is strain-rate dependent (Julian and Lan, 1991; Phillips and Davies, 1991). Pierson (2005) described HCF as an intermediate flow type between streamflow and DF, with a highly suspended, fine sediment concentration, while coarse sediments are transported as bedload. Therefore, they exhibit a turbulent two-phase behavior (Rickenmann, 1991; Manville et al., 2013). Considering the properties of HCF, such as density and viscosity, several authors have defined its behavior as a pseudoplastic fluid flow.

6.1 Modeling Debris Flows and Hyperconcentrated Flows

In recent decades, various computational models have been developed that have allowed simulating the physics of mass flows from the resolution of equations by numerical methods (Iverson, 2014). Computational models or numerical codes have become one of the most important tools for HCF/DF hazard assessment. Thouret et al. (2020), their **Table 4** elaborated on a list of models used for simulating lahars or HCFs/DFs, such as LAHARZ-py (Schilling, 2014), Titan2D (Pitman and Le, 2005; Williams et al., 2008) and Titan2F (Córdoba et al., 2015; Córdoba et al., 2018), FLO-2D (O'Brien et al., 1993), RAMMS (Cesca and D'Agostino, 2008), and VolcFlow (Kelfoun and Druitt, 2005). We tested three models, Titan2F, VolcFlow, and FLO-2D, all shallow-water depth-averaged models for modeling HCFs and DFs in the Qdas. San Lazaro and Huarangal. Assuming that HCF or DF thickness is much smaller than its length, it is possible to integrate the 3D mass and momentum balance equations over depth to obtain the depth-averaged continuum flow equations (Savage and Hutter, 1989). All simulations were performed over the 2013 DSM of the El Misti-Arequipa area (Oehler et al., 2014; Charbonnier et al., 2020) after smoothing and resampling the grid to 4 m spatial resolution and removal of all bridges crossing both Quebradas to avoid artificial blocking of the channeled flows. Charbonnier et al. (2020) used another couple of Pléaïdes images to enlarge the DSM to the SW flank and a TanDEM-X (12 m) to include the NE of the city, Huarangal-MM catchment, and El Misti's summit. This has led to a DSM where bridges and other obstacles have been removed to simulate "free" flows, avoiding artificial damming and thickening of flows in case of

TABLE 8 | Input parameters used to simulate HCFs and DFs with Titan2F numerical code and output parameters for three different scenarios.

Scenarios	Input parameters				Output parameters		
	Volume V	Time	Initial solid concentration	Volume V	Time	Mean velocity v	Volume V
	$\times 10^5$ m^3	Min	Vol%	$\times 10^5$ m^3	Min	m/s	$\times 10^5$ m^3
T1	1.5	240	T1	1.5	240	T1	1.5
T2	3.5	240	T2	3.5	240	T2	3.5
T3	5.0	240	T3	5.0	240	T3	5.0

artificial obstacles. We also ran simulations using the original DTM in which bridges and obstacles were present: the artificial obstacles (i.e., bridges digitally represented as vertical walls) dammed channeled flow deposits and induced artificial overbank flows with high velocities (5–7.5 m/s). Based on the outputs of the computational models, we defined mass-flow inundation zones, flow depths, and dynamic pressure and compared the results from the three codes despite their different purposes and input parameters.

The computational models require several input parameters (either from measurements in river channels and flumes, empirical models, or literature) and initial and boundary conditions, which are different for the three models (**Table 7**). In order to apply reliable rheological models to the modeled flows, we defined the density, viscosity, and yield strength parameters for each type of flow. Among required input parameters, flow rate and sedimentation concentration are critical for simulating sediment-water flows. Despite the lack of recorded flow discharges (except for streamflows and a few recent events, e.g., the 8 February 2013 HCF), we estimated discharges for both Quebradas based on the available discharge data of Río Chili and the Gumbel law distribution (**Section 5.1**; **Table 6**). The paucity of sedimentation concentration values makes it difficult to apply rheological properties and determine flow behavior, representing critical input information for modeling. Pallares et al. (2015) found high sand and gravel contents and a minimum amount of fine particles in historical lahar deposits across the city of Arequipa, although it is known that the grain-size distribution of lahar deposits does not reflect the wide flow spectrum that emplaced them (Dumaisnil et al., 2010). In case of heavy rainstorms (≥41 mm/h) over the small catchments under study, erosion and incorporation of coarse-grained volcaniclastic deposits to lahars may produce a limited increase in fine-grained particles (<8% silt and clay; Pallares et al., 2015). A small proportion of clay and silt in flows would influence the behavior of less cohesive HCFs and DFs (Bardou et al., 2007). Thus, we derived additional physical and rheological parameters of the flows to be simulated from previous studies of lahar characteristics at Sarno, Italy (Zanchetta et al., 2004); Mt. Ruapehu, New Zealand (Manville et al., 1998); Semeru, Indonesia (Dumaisnil et al., 2010; Doyle et al., 2010, 2011); and Panabaj, Guatemala (Charbonnier et al., 2018). HCFs prevailed among lahar flows and deposits measured around Semeru, which provided characteristics similar to recent flows observed in Arequipa, such as the 8 February 2013 HCF (Ettinger et al., 2015).

We mapped scenario-based inundation zones and evaluated impacts on the building stock using simulation runs of real and potential mass flows obtained from the three numerical codes. Three scenarios for HCFs and DFs have been derived from the recorded small-to-moderate events with ⊢ 1.5×10^5 m^3 (e.g., the 8 February 2013 HCF) and moderate-to-large historical lahars (c. 2.5 m^3– 3.5×10^5 m^3 to 5×10^5 m^3).

6.2 Simulations Using Titan2F

Titan2F was developed at SUNY University at Buffalo for the modeling of biphasic (sediment-water) gravity-driven flows. The Titan2F model uses a similar framework to that developed by Pitman and Le (2005) for Titan2D. However, Titan2F has a complete set model of equations for both the granular phase and fluid phase (Córdoba et al., 2015; Córdoba et al., 2018). Titan2F is based on a depth-averaged, shallow layer model, as the fluid phase of the flow is modeled using a typical shallow water layer approach, while the frictional behavior of the solid phase is accounted for during the propagation of the simulated flow by assuming the Mohr–Coulomb model (Savage and Hutter, 1989).

6.2.1 Input and Output Parameters for Titan2F

In order to simulate sediment-water flows using Titan2F, a limited number of input parameters is required: 1) initial location and volume of the pile of debris, which collapses by gravity only upstream of the drainage channel that conveys flows; 2) initial solid concentration; 3) simulation time; and 4) volume (**Table 8**). Volumes ranging from 1.5 to 5×10^5 m^3 correspond to flow volumes derived from past and recent inundation areas within the city, geological mapping of lahar deposits in El Misti's drainage network, previous modeling obtained with LAHARZ (Delaite et al., 2005) and Titan2D codes (Vargas-Franco et al., 2010; Martelli, 2011; Pierson, 2005). Internal and basal friction angles vary during the flow propagation according to the variable solid concentration (Córdoba et al., 2015; Córdoba et al., 2018). The range of basal friction angles was 8°–18° in DFs simulated in Río Chili with Titan2D (Martelli, 2011). Internal friction angle ranges between 20° and 33° in simulations, lower than friction angles of the gravel- and sand-rich lahar deposits from El Misti (35°–38°, Pallares et al., 2015). The parameter of friction angles in lahar flows, as simulated with Titan2D, is directly incorporated in the Titan2F code, as the initial high frictions values of the Titan2F piles at the source decrease down valley according to the evolution of the solid concentration in time and space. If the solid concentrations become too low, the water-phase laws

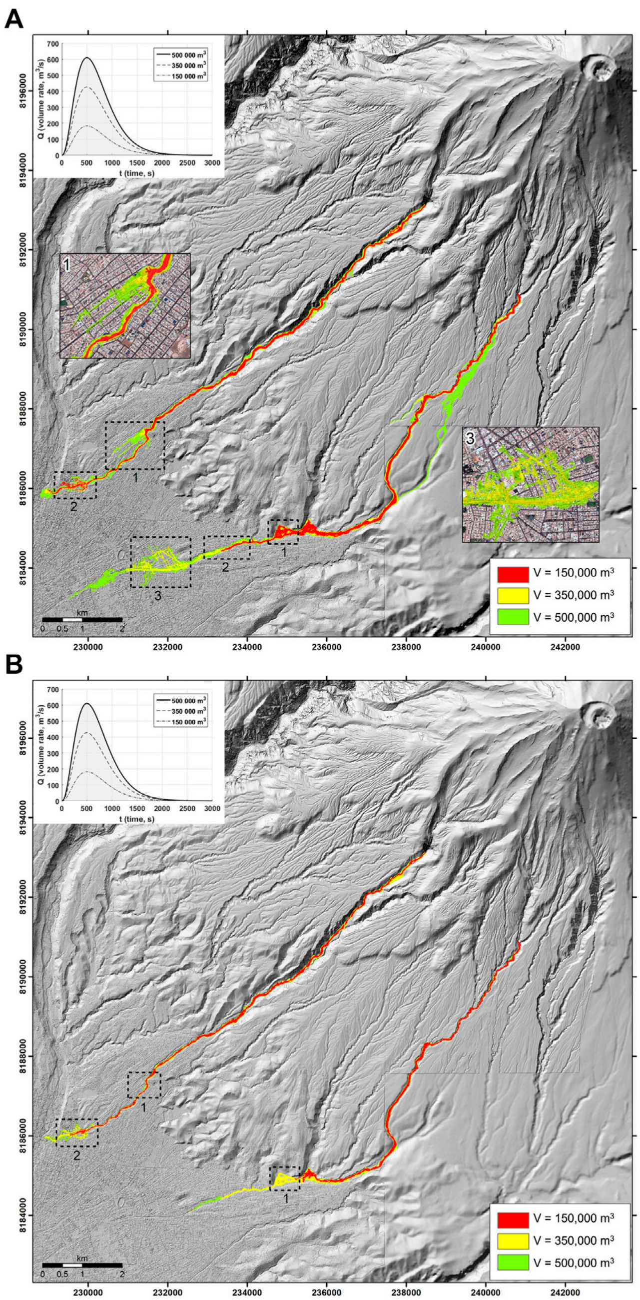

FIGURE 5 | VolcFlow simulation results using three HCF and DF scenarios with 0.15, 0.25, and 0.5 × 10^5 m^3 (**Table 8** for input and output parameters). Extent of simulated flows and overbank areas for HCF **(A)** and DF **(B)**. Dynamic pressure of HCF **(C)** and DF **(D)** in the middle reach of Qda. San Lazaro. Inset diagram shows the hydrograph used for three volumes of HCFs and DFs.

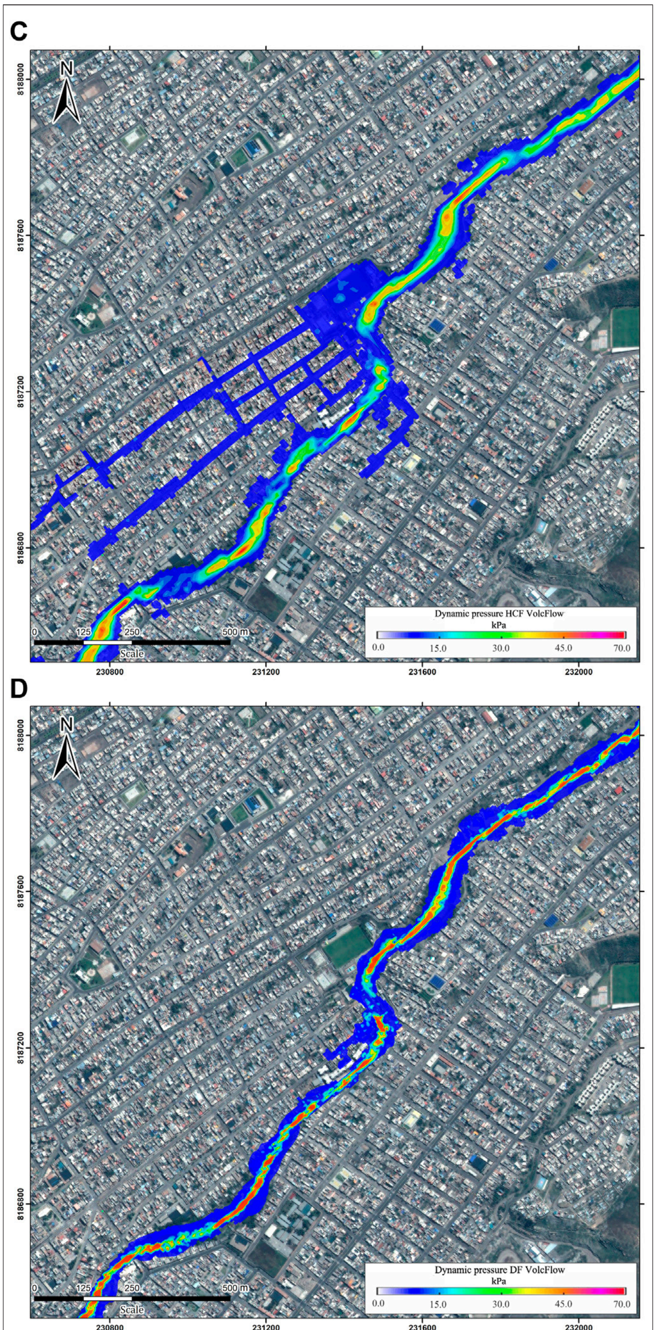

FIGURE 5a | *(Continued)*

become dominant over the friction-based solid phase (Córdoba et al., 2018).

Three scenarios (**Table 8**) were modeled using Titan2F with variable input parameters: three volumes, a duration of 240 min based on the database of flows observed in Arequipa (**Supplementary Table S1**), initial solid concentration typical of HCFs, and no initial velocity (**Table 8**). The worst-case scenario is assumed to result from the combination of the maximum volume (5 × 10^5 m^3) with the maximum solid concentration (30%–40% volume), based on large-scale historical lahars. Successive runs of three different volume flows were made on the DTM to delineate run-out zones and determine flow depth, velocity, and dynamic pressure.

Simulated flow depths and mean velocities are comparable with values observed in the 1915–2020 database and within the

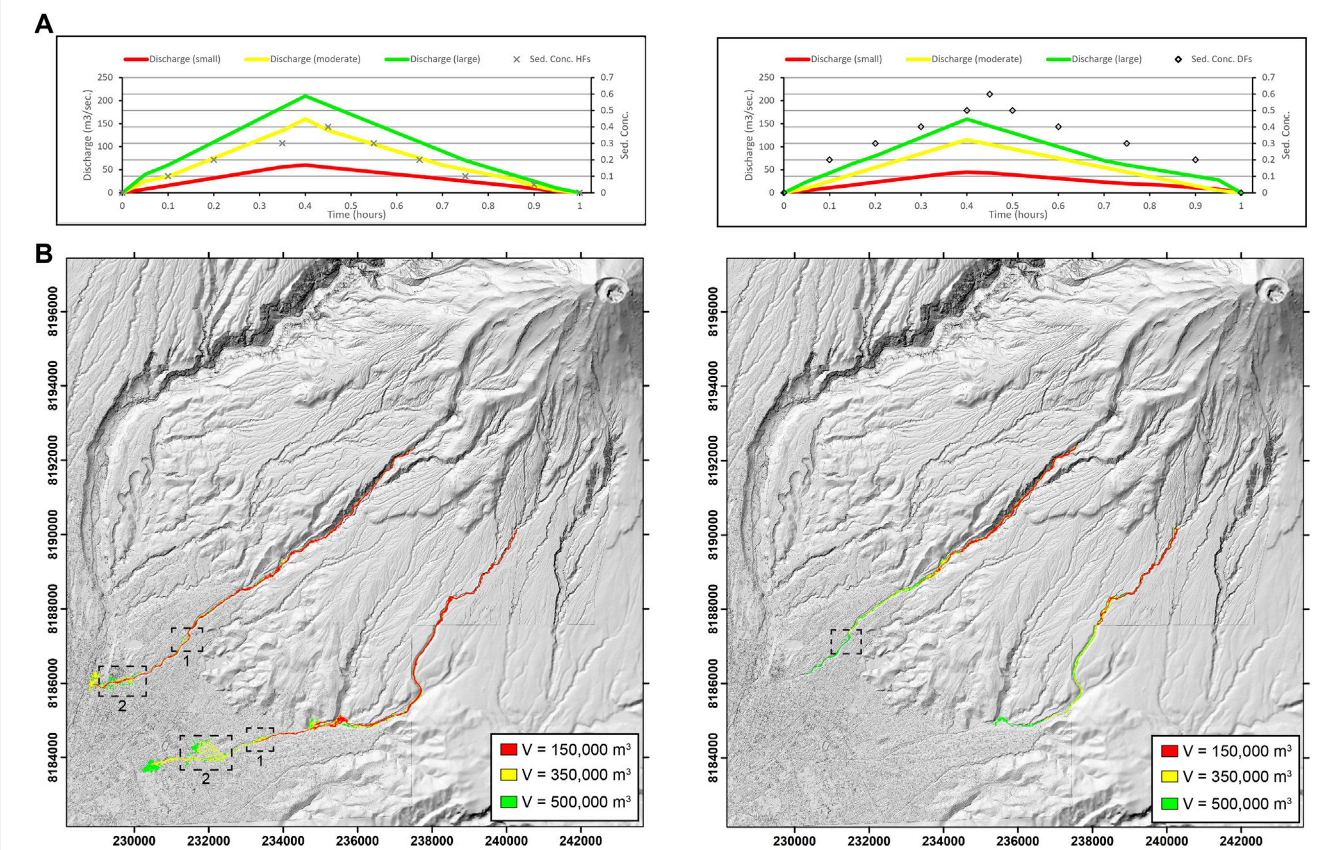

FIGURE 6 | FLO-2D simulation results for three HCFs (to the left-hand side) and three DFs (to the right-hand side) events in the San Lazaro and Huarangal catchments. **(A)** Inflow hydrographs for the three HCF and DF events considered: small-volume (red), moderate-volume (yellow), and large-volume (green). Sediment volumetric concentrations are also shown. **(B)**. Inundation map of the three simulated HCFs (left) and DFs (right). Dashed black rectangles and numbers show the major overbank areas along both catchments (see text for explanation).

low range of depth and velocity values reported in the aftermath of the 2013 HCF in the Qda. Venezuela. There, the velocity values were estimated based on equations of superelevation at channel bends (5.9–10.9 m; Ettinger et al., 2015). The mean velocity range of simulated flows remains comparable with the majority of HCFs and DFs measured in the Koboan–Lengkong River channels at Semeru (Doyle et al., 2010; Doyle et al., 2011), where rain-triggered, coarse-grained HCF pulses lasted for 1–3 h with heights of 0.5–2 m, peak velocities of 3–7 m/s, and discharges of 25–250 m^3/s.

Figures 4A,B show that simulated flows remain entrenched in ravine channels but spread out down valley in the dense urban area at the break in slope between the volcaniclastic fan and the Río Chili high terrace upstream of the historic center. Titan2F-based simulations did not show flow overbanks at sharp bends in the San Lazaro middle reach near the J. Olaya bridge with a moderate volume of 3.5×10^5 m^3 (**Figures 2A**, **4B**). Overbank areas, shown as rectangles 1–3 down valley (**Figures 4A,B**), correspond to sharp bends and change in slope in the ravine channel near el Golfo bridge, as well as damming and runup effects at the confluence with Río Chili. Despite wall containment 1.3 km upstream of the confluence with Río Chili, overbanks occur along Qda. San Lazaro due to the narrow channel capacity and constriction upstream of bridges. Along Qda. Huarangal-MM, the HCF and DF extent is more limited down valley: the 1.5×10^5-m^3 flow is restricted to the upper reach, while the 2.5–5 × 10^5-m^3 flows propagate to the middle reach only. Simulated overbanks also occur along the Qda. MM (Mariano Melgar) channels, which become narrower (10–20 m) and shallower (3–5 m) downstream of the bridge 8 de Octubre (**Figures 2B**, **4A,4B**). Noteworthy, the simulated flows spread out laterally upstream of that bridge onto two areas on the north side of the middle reach, coinciding with the inundated areas of the San Geronimo lahar in 2011.

Simulated dynamic pressure values along the San Lazaro channel (**Figure 4C**) show a range from 5 to 35 kPa with high (20–35 kPa) values concentrated in the middle of the channel. Dynamic pressure values of 20–25 kPa are significant on the channel edges and low terraces. Pressures as high as 35 kPa can cause significant damage to low-quality houses, and the most vulnerable building classes A0 and A are located on the adjacent low terraces (**Supplementary Figure S2**). Structural houses of types 1, 1A, 1B, and 2A, 2B on the channel edge can be destabilized and damaged by flows with modest (20 kPa) to high (35 kPa) dynamic pressure.

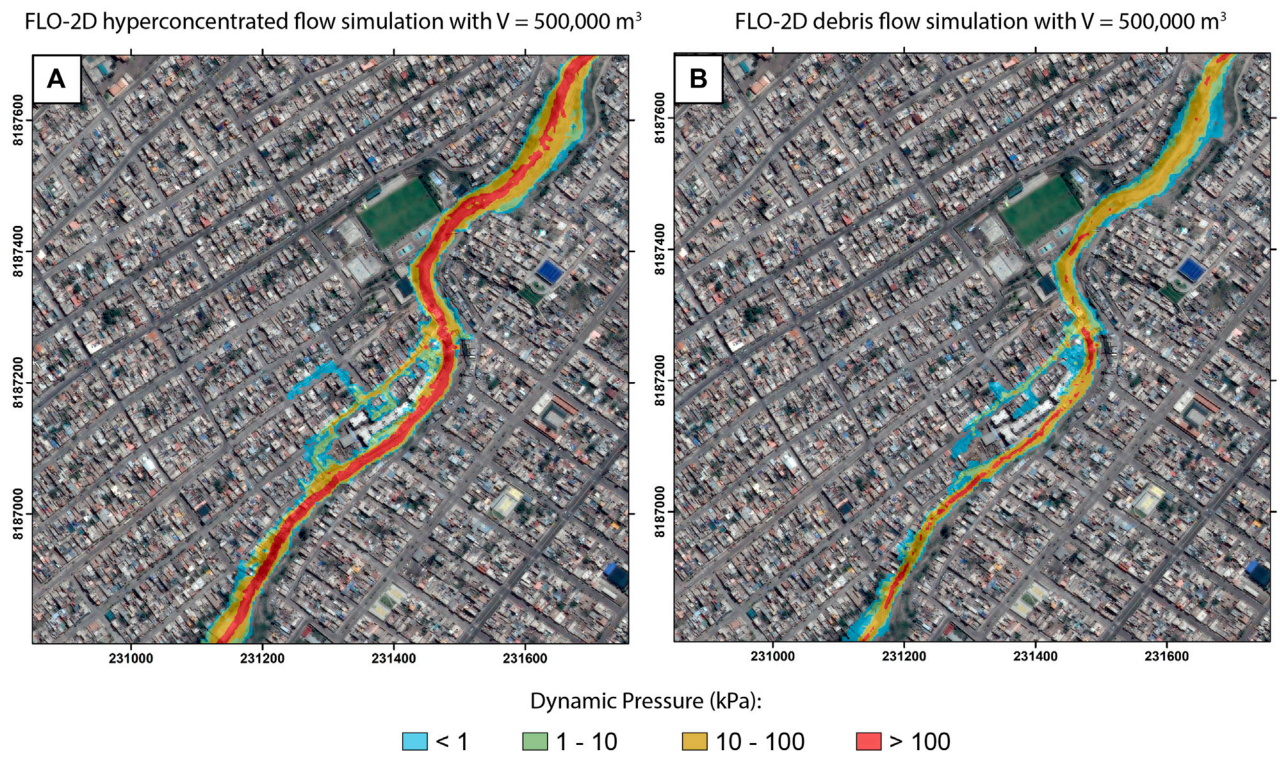

FIGURE 7 | Maps of simulated dynamic pressure (in kPa) obtained from FLO-2D simulations in a channel section (J. Olaya bridge linking the Miraflores and Alto San Alegre districts) of the San Lazaro catchment for **(A)** HCF and **(B)** DF, both with a volume of 5 × 10^5 m^3.

TABLE 9 | Input parameters used to simulate HCFs and DFs with VolcFlow numerical code and output parameters for three different scenarios. The parameter c is constant for all simulations and equals to 0.001.

Scenario		Input parameters					Output parameters		
		Volume *V*	Time	Density *ρ*	Yield strength τ_0	Viscosity *μ*	Flow depth *h*	Mean velocity *u*	Dynamic pressure *Pdy*
		×10^5 m^3	Min	kg/m^3	Pa	Pa.s	M	m/s	kPa
VF1	HCF	1.5	60	1,300	1	0	0.1–2.5	1.0–3.0	2.0–26.0
	DF	1.5	240	1900	100	10	0.2–2.5	1.0–3.4	2.0–26.0
VF2	HCF	2.5	60	1,400	20	1	0.3–3.5	1.0–5.2	2.0–31.0
	DF	3.5	240	2000	100	10	0.4–4	1.0–6.0	3.0–36.0
VF3	HCF	4.5	60	1,600	20	1	0.5–4.0	1.0–7.0	4.0–50.0
	DF	5.0	240	2,200	200	20	0.5–4.6	1.0–7.5	6.0–61.0

6.3 Simulations Using VolcFlow

VolcFlow was developed at the Laboratoire Magmas et Volcans to simulate the complex behavior of volcanic flows (Kelfoun and Druitt, 2005; Kelfoun et al., 2009; Kelfoun, 2017). It is based on the shallow water depth-averaged equations of mass and momentum balance, and the code allows the use of different rheological laws and source conditions. The equations are solved in a MATLAB® environment using a numerical method based on an Eulerian scheme by finite difference. The input parameters are the volume rate with time, and the flow is defined as a viscoplastic Bingham fluid (Rickenmann, 1991; Phillips and Davies, 1991; Julien and Lan, 1991; Major and Pierson, 1992) with a yield strength and viscosity (**Table 9**), combined with a turbulent-dispersive law that considers the effects of turbulence and dispersive stresses caused by sediment collisions. In the depth-averaged form, it is expressed as follows:

$$\boldsymbol{\tau} = \tau_0 \times \frac{\mathbf{u}}{\|\mathbf{u}\|} + 3 \times \mu \times \frac{\mathbf{u}}{h} + c \times \rho \times \mathbf{u} \times \|\mathbf{u}\|, \quad (1)$$

where τ_0 is the yield strength, μ is the viscosity, ρ is the flow density, h its thickness, and $\mathbf{u} = (u_x, u_y)$ its velocity. The coefficient c is a

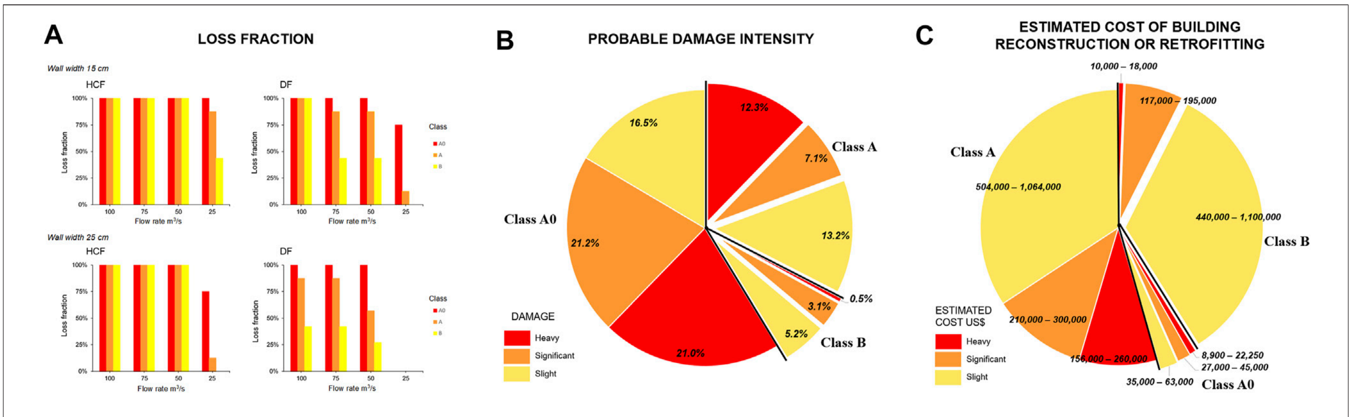

FIGURE 8 | (A) Loss fraction of buildings of classes A0, A, and B in case of DF and HCF for two wall widths of 15 and 25 cm (adapted and expanded from Mead et al., 2017). We expanded the 2017 study to all buildings located along both sides of both ravines under study within a distance of 50 m (maximum 100 m) from and an elevation of 5 m (maximum 10 m) above the channel. Numbers of buildings in class A0 = 249, class A = 138, and class B = 37. **(B)** Probable damage intensity considered three levels of damage: slight (impacts on walls, external elements, and roofs), significant (structural deficiency), and heavy (collapse) according to the location with respect to the channel and delineated area of dynamic pressure (**Figures 4C**, **5C**, **8**). Damaged buildings of class A0 (heavy 89, significant 90, slight 70); class A (heavy 55, significant 30, slight 53); and class B (heavy 2, significant 13, slight 22). **(C)** Estimated cost of reconstruction and/or retrofitting considered building classes A0, A, and B according to levels of damage. Cost is based on actual (2018–2019) construction value per m^2 in Arequipa but does not correspond to the commercial value based on age, location, maintenance of the building, and quality of the neighborhood.

dimensionless number that can be linked to the coefficient ξ of Voellmy ($c = \frac{g}{\xi}$) and that rules the turbulent dispersive pressure. The VolcFlow version used here is the single-phase version, in contrast to the two-phase regime used by Titan2F and FLO-2D codes.

Other input parameters used in VolcFlow are as follows (**Table 9**): 1) the same 4 m resolution DSM of the Arequipa area used for other codes and 2) an inflow hydrograph (inset, **Figures 5A,B**) imposed as a boundary condition and based on the measured rainfall amount and values of water and sediment discharge (yielding a flow volume). For this study, the volume rate Q of the hydrograph is approximated by the following law:

$$Q = k_1 \times t^{k_2} e^{-t/k_3}, \quad (2)$$

where $k_2 = 2.5$, $k_3 = 200$, and k_1 is computed to obtain the total flow volumes ranging from 1.5×10^5 m^3 to 5×10^5 m^3. Given these parameters, the volume rate increases to reach a peak discharge at 500 m^3/s and then decreases exponentially during ~2,000 s. The physical and rheological values, shown in **Table 9**, have been selected from empirical and experimental values calculated by Rickenmann (1991), Phillips and Davies (1991), Pierson (2005), Iverson et al. (2010), Iverson et al. (2011), and Manville et al. (2013).

Modeling scenarios were established for a set of HCFs and DFs in both Qda. San Lazaro and Huarangal (**Table 9**). In total, three scenarios, each including two types of mass flows, were defined for both ravines with a similar range of volumes (1.5–5 × 10^5 m^3). We assume the worst-case scenario WF3 to be the result of maximum volumes (4.5 to 5 × 10^5 m^3) with a density of 2,200 kg/m^3, yield strength between 20 and 200 Pa, and viscosity between 1 and 20 Pas (**Table 9**). This scenario represents HCF and DF events triggered by heavy, durable rainstorm remobilizing abundant, loose material emplaced by post-eruptive lahars.

The results of numerical simulations corresponding to HCF showed a realistic extent of the impacted areas (**Figure 5A**) and reasonable values of velocity and flow depth compared to the observed flows from the database. However, overbanks were observed at the large bend, followed by channel constrictions near the J. Olaya bridge in the middle reach of Qda. San Lazaro (**Figure 2A**) when the hydrograph reaches a maximum flow rate of 500 m^3/s (inset **Figures 5A,B**).

The distribution of hydrodynamic pressures is between 35 and 100 kPa (**Figure 5C**) across the channel and low terraces 2–4 m high, where the most vulnerable houses (classes A0, A, and B) are located. For volumes in the order of 2.5–3.5 × 10^5 m^3, the large-volume scenario shows that major overbanks occurred from a sharp bend located just upstream of the José Olaya bridge and another just upstream El Progreso bridge (**Figures 2B**, **5B**).

6.4 Simulations Using FLO-2D

FLO-2D (FLO-2D Software Inc, 2021; O'Brien et al., 1993) is based on depth-averaged continuum flow equations. This code models lahar rheology using a shear stress relationship, and this rheology depends on the sediment concentration and flow mass, which vary during the flow propagation. Details about the code itself can be found in O'Brien et al. (1993), while the FLO-2D code was applied, for instance, by Charbonnier et al. (2018) to simulate the 2005 lahars at Panabaj (Guatemala). Two separate case studies are investigated here for the emplacement of 1) three DFs in the San Lazaro and Huarangal catchments and 2) three HCFs in the same catchments. The DFs and HCFs separately exhibited the same rheology and sediment concentration (i.e., all DFs were the same and all HCFs were the same). However, they each had three different volumes/discharges corresponding to small-, moderate-, and large-volume events.

FLO-2D includes various input parameters: 1) the DTM/DSM of the study area; 2) an inflow hydrograph based on measured rainfall accumulation and values of water and sediment discharge (i.e., flow volume); 3) a range of Manning roughness coefficients (0.03–0.08 according to the channel geometry and material); 4) yield strength and dynamic viscosities expressed as a function of the volumetric sediment concentration:

$$\tau_y = \alpha_i e^{\beta iCv}, \quad (3)$$

$$\eta = \alpha_j e^{\beta jCv}, \quad (4)$$

where τ_y is the yield strength, η is the dynamic viscosity, C_v is the volumetric sediment concentration, and $\alpha_{i,j}$ and $\beta_{i,j}$ are two empirical coefficients obtained from O'Brien and Julien (1988) for HCFs and DFs with similar characteristics as the Misti ones; (5) the dimensionless laminar flow resistance K (**Table 7**); and (6) a Froude number, a dimensionless value defined as the ratio of kinetic energy to the potential energy that also accounts for the effect of gravity (**Table 7** for best-fit input values). Inflow hydrographs for each simulation are shown in **Figures 6A,B**. Peak discharge rates (water only) vary from 45–60 m^3/s (small-volume events) to 160–210 m^3/s (large-volume events) for both DF and HCF simulations, while peak sediment volumetric concentrations (attained after ~25 min) are set at 60 and 40 vol% for DF and HCF runs, respectively. Flow volumes vary between 1.5×10^5 m^3 (small-volume events) and 5×10^5 m^3 (large-volume events). Following Charbonnier et al. (2018), the Manning roughness coefficients vary with channel geometry and roughness between 0.03 and 0.08, the laminar flow resistance is set at 400, and the extended Froude number at 0.9 and two different rheological parameters ($\alpha_{i,j}$ and $\beta_{i,j}$) were used to simulate the differences in yield strengths and viscosities of DFs *versus* HCFs (**Table 7**). Inundation maps for the DFs and HCFs are shown in **Figures 6A,B**, respectively.

FLO-2D model results (**Figures 6A,B**) highlight the contrasting behavior of HCFs compared to DFs. Runout distances of the three simulated DFs (**Figure 6B**) do not exceed 16 km, and flows are confined to the main river channels only, except for a flow overspill that occurred in a sharp bend located just before the J. Olaya bridge (Miraflores district) in the Qda. San Lazaro (dashed black rectangle area in **Figure 6B**). In contrast, runout distances of the three simulated HCFs (**Figure 6A**) vary between 17 km (small-volume event) and >20 km (moderate-to-large-volume events), and major overspills from both sides of the San Lazaro and Huarangal-MM channels occurred between 15 and 20 km runout distances (dashed black rectangle areas in **Figures 6A,B**), with the moderate- and large-volume scenarios (volume $\geq 3.5 \times 10^5$ m^3) flooding the neighboring streets next to both Quebradas with <4 m thick water-rich HCFs. Along the San Lazaro channel section passing through the city of Arequipa, the major HCF overspills (up to 300 m in width) occurred at runout distances between 16.5 and 17.5 km (overbank area two in **Figure 6A**), in areas of channel constriction, first at the El Progreso bridge and in the Selva Alegre and Historic Center districts. Along the Huarangal-MM channel in Arequipa, a minor overspill (<130 m width) occurred first along an area of channel constriction due to the presence of the Tupac Amaru bridge (overbank area one in **Figure 6A**). Then, a major overspill occurred ~1 km downstream of the Santa Rosa bridge, flooding the streets on the NW area up to 800 m away from the Qda. Huarangal-MM (overbank area 2 in **Figure 6A**). Flow overspills located at the distal end of both Quebradas (before reaching the Río Chili in the San Lazaro and in the Explanada Dolores (a meeting square for public events) in the Huarangal-MM, are due to the poor resolution of the topography on the DSM in these areas, mostly due to the presence of trees.

These first FLO-2D modeling results at Misti highlight that while DFs are mostly confined in the main river channels, impacted areas of moderate-to-large-volume (>3.5×10^5 m^3) HCFs in the city of Arequipa can be extensive and dangerous. HCFs can spill over from the shallow and narrow riverbeds and inundate highly populated streets and critical city roads and bridges.

7 DISCUSSION

The numerical simulations show acceptable results as they can reproduce the extent of the areas impacted by mass flows from the 1915–2020 database. Three computational models used for evaluating the propagation of HCFs and DFs can delineate and forecast the potentially flooded and overbank areas.

7.1 Uncertainties and Limitations Linked to Simulations

Uncertainties and limitations associated with tephra-fall scenarios and modeling have already been addressed in Sandri et al. (2014). The authors considered the natural variability of the eruptive process in terms of eruptive sizes and vent location. Many possible scenarios were combined, each one weighted with its own probability of occurrence. This allowed the authors to quantify how the uncertainty in the eruptive size and vent location affected the probability for different areas around the volcano to be impacted in a given time window: the associated hazard. Herein, uncertainties are linked to the choice of two hazard metrics: the tephra load of 100 and 250 kg/m^2. The first choice was driven by the poor-to-moderate resistance of the majority of the roofs in the surveyed neighborhoods along the San Lazaro ravine. The majority of flat roofs and the paucity of pitched roofs across Arequipa reduces the roof resistance. As the probability of ashfall toward the city increases during the rainy season, one of the study limitations stems from the fact that the rainfall was not included in the tephra-fall scenario. Wet tephra will have a considerable effect on the metal sheet and hybrid roofs if the latter are not cleaned during the eruption.

Input parameters of the three numerical codes cannot be used for benchmarking purposes. However, we can compare outputs (extent, paths, overbank areas, velocity, and flow depth) with characteristics reported from the most recent flow events. All three codes did a good job in reproducing observed flows, particularly recent HCFs across two basin ranges in Arequipa, which are the most common events from the database 1915–2020. Simulation runs show the expected path and extent along the entrenched ravine channels, particularly Qda. San Lazaro. All runs show overbank areas down valley at sharp bends, break in slope between volcaniclastic fans, and upstream of narrow bridges. In the Qda. Huarangal-MM, the most voluminous DFs and HCFs only can reach the densely populated neighborhoods along the middle and lower reaches. This is due to the long (16 km) path and gentle slope down valley, and Titan2F simulated flows are shorter than other flows simulated with VolcFlow and FLO-2D. The shorter inundated areas may be due to at least three factors: 1) the Mohr–Coulomb model prevents the flow from propagating on slopes below the lowest basal friction angles chosen as input; 2) viscosity, allowing the flow to propagate on gentle slopes, is not considered in Titan2F; and 3) the initiation process is not a mass flux, but a pile of material which collapses due to gravity.

Titan2F-simulated flows display a narrow extent, shorter paths, particularly in the Qda. Huarangal-MM, and a limited number of overbanks with respect to documented channel sinuosity and constrictions. VolcFlow- and FLO-2D-simulated flows exhibit longer and/or wider paths, higher velocity, and overbanks in the same areas at bends and down valley, which pinpoint reaches where attention must be drawn for mitigation measures to be implemented (containment wall, check dams, or enlargement of bridges). VolcFlow and FLO-2D reproduce overbank at the Olaya bridge bend in the middle reach of San Lazaro that does not appear with Titan2F runs.

The outputs of all three codes included flow depth, velocities, and dynamic pressure. Ranges of flow depth (0.1–4.6 m) and velocities (1–9 m/s) are comparable between codes and real flows and with simulated flows in the literature, whereas the distribution of dynamic pressure differs between the code outputs. Dynamic pressure has never been measured during or immediately after flows in Arequipa. By considering the same middle reach of the Qda. San Lazaro, the range of dynamic pressure is narrower with Titan2F runs (0–50 kPa), widens to 75 kPa with VolcFlow runs, and expands beyond 100 kPa with FLO-2D runs. VolcFlow- and FLO-2F-simulated HCF and DF display a wider area impacted by dynamic pressure on both sides of the ravine channel, extending onto the low terraces or banks on which low-quality buildings are located (**Figures 5C**, **7**). Usually, HCFs exert a weaker dynamic pressure range than DFs, but FLO-2D-simulated HCFs show a higher dynamic pressure range (**Figure 7**).

By using FLO-2D, density is automatically computed according to the specific weight of the flow, which varies progressively as the flow propagates down valley. Density values can be much higher in HCFs than DFs in channels; in contrast, density is an initial parameter within Titan2F and VolcFlow and does not change down valley. In terms of rheology, HCFs mostly displayed the highest dynamic pressures acting on parallel walls (Mead et al., 2017). The higher density (compared to Newtonian flows) is responsible for the larger dynamic pressures (Jenkins et al., 2015). This effect is moderated by the yield strength of HCFs, causing the velocity to be lower than Newtonian flows near perpendicular walls. DF pressures are much lower than both Newtonian and HCFs as the yield strength and dilatant rheology components limit overbank flow velocities.

From estimated values of lahar impact pressure in Sarno, Italy, Zanchetta et al. (2004) argued that the complete destruction of a building required a pressure exceeding 90 kPa. Below this value, structures were generally heavily (35–90 kPa) or moderately (<35 kPa) damaged. The required pressure to break a large single-glazed window was as low as 1–2 kPa, and it was little more than 3 kPa for a wooden door. Therefore, an important point is that openings are the weakest points of buildings and are a critical parameter to quantify in buildings surveys. The dynamic pressure threshold of 35 kPa (Zanchetta et al., 2004) for moderate damage would be the case along both ravines for flows simulated with Titan2F and VolcFlow. The dynamic pressure threshold of 90 kPa for severe damage has been reached along both channels, as shown by HCFs and DFs simulated with FLO-2D. Heavy damage triggered by dynamic pressure between 35 and 90 kPa can be attained in the channel center and along sharp curves and/or narrow sections (e.g., upstream and near the J Olaya bridge; **Figures 5C**, **7**). In all cases, the high (30%–50%) proportion of openings, the prevailing single-glazed windows in surveyed buildings in Arequipa, represent the weakest point for HCF and DF impacts in Arequipa.

7.2 Impacts of Tephra Fall on Roofs

The evaluation of tephra load on roofs has shown that at least 50% of building roofs of classes A0, A, and B are highly vulnerable to tephra load of 250 kg/m^2, a force of 2 kN/m^2. This is equivalent to a 10-cm-thick tephra that would fall in the rainy season over the city. As future El Misti eruptions would likely produce 10- to 50-cm-thick tephra-fall deposits, the probabilities of roof collapse would affect at least four among the nine categories of roofs.

Considering the cost of roof collapse, the low quality of roofs, and the low-income households in the surveyed neighborhoods, retrofitting and construction need to be undertaken by the municipality, the regional government, and NGOs. Specific construction rules and prevention procedures should be implemented as soon as El Misti awakens and before an imminent eruption.

7.3 Impacts of Mass Flows on Habitat and Loss Evaluation

Damage from water-rich flows is induced by a combination of three principal forces: 1) hydrodynamic pressure, 2) hydrostatic pressure, and 3) the collisional force of boulders (Thouret et al., 2020, and references therein). Hydrodynamic pressure exerted by the flow front/head, having horizontal and vertical components, is the kinetic energy per unit volume of the flow, which changes with flow density. Hydrostatic pressure depends on the depth and weight of the wet flow until it solidifies and acts toward the end of the event once the deposit is stabilized. Herein, we will not consider boulders, which act like missiles, hitting structures, and obstacles. Hydrodynamic pressure is proportional to the square of the frontal velocity as follows:

$$Pdy = k\rho d f v^2, \tag{5}$$

where Pdy is the dynamic pressure; k is a constant, which depends on the density of the granular material, flow dynamics, and flow homogeneity and constituents; ρdf is the mean density of the mixture; and v is the velocity of the flow front.

Zeng et al. (2015) distinguished three principal damage categories for reinforced concrete and masonry structures by linking flow processes with hazard intensity: 1) inundation or burial, including damage to the ground floor or external walls of a building together with debris entering rooms, but without significant damage to structural components; 2) serious structural damage owing to flow front impact or boulder impacts triggering the failure of single structural elements, or the collapse of the whole structure; and 3) undercutting where soil erosion and/or liquefaction deforms foundations and subsequently buildings tilt or collapse. Faella and Nigro (2003) and Nigro and Faella (2008) stated that the severity of LH/DF impacts largely depended on the orientation and structural types of edifices and the kinetic energy of flows (a function of velocity, density, and Froude number).

From the evaluation of fragility curves by Mead et al. (2017) in the Qda. Dahlia, a tributary of Qda. Huarangal, we elaborated fragility curves for 425 buildings surveyed in 2018 and 2019 along the Qda San Lazaro and Huarangal. Fragility curves (**Supplementary Figure S4** taken from Mead et al., 2017) were adapted and expanded to all surveyed buildings of classes A0, A, and B along both quebradas. Fragility curves based on hydrodynamic pressure and flow depth indicate to which extent buildings of classes A0, A, and B with wall bricks of 25 and 15 cm width would be affected by the ultimate bending moment before collapsing. The ultimate bending moment

$$Mu = (ft + fd)wb2/6, \tag{6}$$

where *ft* is the tensile strength of the masonry wall, *fd* is the design compressive stress acting on the wall, w is the width of the wall facing the flow, and b is the thickness of the wall.

Brick walls (and "bloquetas," i.e., lapilli-rich rubble stones) represent about 60% of the buildings in these areas. **Figures 5C**, **7** and **Supplementary Figure S4** suggest that moderate dynamic pressure in the range of 20–30 kPa and flow depth <1.5 m would suffice to bend the 15-cm-thick and 25-cm-thick brick walls, respectively.

Figure 8A, adapted and expanded from Mead et al. (2017), shows the loss fractions of buildings having brick walls (15 and 25 cm thick, respectively) due to HCF and DF with flow rates as low as 25–100 m^3/s. Three out of four flow rate values (25, 50, and 75 m^3/s) considered in the loss evaluation of buildings of classes A0, A, and B correspond to the 5- to 10-year return period of flow events in Arequipa (**Table 6**), to be compared with flow rates in the order of 125 m^3/s during the 8 February 2013 HCF in Qda. Venezuela, which represents a 50-year return period flow according to **Table 6**. The loss proportion of all class buildings is 30% higher for the brick wall of 15 cm thickness when HCFs are considered with respect to DFs. For the 15-cm-thick brick walls, the loss proportion of class A0 buildings is high (75%–100%) in all HCF and DF cases, the loss proportion of class A buildings is relatively high (85%–100%) in case of HCF but less in case of DF (10–85%). The loss is relatively minor (0%–40%) for class B buildings in case of DF except for flow rates ≥100 m^3/s and substantial (45%–100%) in case of HCF. As a result, a substantial loss of low-quality buildings on both sides of the ravines in Arequipa would result from HCFs within the range of 5- to 10-year return period of low-to-moderate (25–75 m^3/s) flow rates.

7.4. Toward an Assessment of Monetary Cost

The monetary cost of loss fractions of buildings has been estimated according to flow scenarios to contribute to planning emergency procedures and civil defense works. The range of cost has been estimated for each structural type of building (**Table 3**; **Figure 8C**). Evaluating cost is challenging in Arequipa because financial issues are a sensitive subject, particularly in city suburbs, where the declaration of assets is biased and tax evasion is omnipresent. **Figure 8C** displays the estimated cost range of construction/retrofitting of each building type, which is not the market value, depending on construction age and location, use, maintenance, and other factors. The estimated cost range (**Figure 8C**) is based on damage level proportions of building classes (**Figure 8B**). Class A0 buildings show the highest (16%–21%) damage levels in all categories (heavy, significant, and slight). Class A buildings display moderate (7%–13%) damage levels in almost all categories, while class B buildings exhibit low (0.5%–5%) damage levels. In terms of monetary cost, the situation is the opposite, as the most vulnerable class is low quality and "cheap" housing. Thus, the estimated cost of reconstruction or retrofitting of damaged class A0 buildings is quite low (0.7%–2.2%). The estimated cost of damaged class A buildings is moderate to substantial (9.7%–32.9%), while the cost of less damaged but regular-quality class B buildings covers a wide range between low (0.6%) and high values (34.1%), which is explained by the fact that a small proportion (<5%) of class B buildings would suffer severe or significant damage.

Should a prevention policy be implemented in the near future, we suggest that houses of classes A0 and A bordering the ravines could be relocated on high terraces at a minimum distance of 250 m away from the channel. Alternatively, the financial and logistical support of the Municipality, Regional Government, Ministry of Housing, and NGOs would allow the reconstruction of houses of classes A0 and A, for example, in the SE basin of Arequipa away from the ravines and El Misti (Municipalidad Provincial de Arequipa, 2011). A large proportion of severely and significantly damaged class A buildings should be reconstructed, while the slightly damaged proportion should be retrofitted. Class B buildings, probably slightly damaged in small proportion, can be retrofitted. Wall containment at sharp bends and enlargement of bridge arches in constricted channels are recommended where overbank flows were simulated and actually occurred in the past.

CONCLUDING REMARKS

The work presented here has assessed the impacts of potential tephra fall and recent mass flows along two ravines that cross the city of Arequipa.

1) The evaluation of tephra load on roofs has shown that a substantial 11%–38% of low-quality and hybrid roofs

would be severely affected when considering the lowest hazard metrics (100 kg/m^2, i.e., 1 kN). This corresponds to the low magnitude/moderate frequency scenario, involving a tephra-fall deposit at least 10 cm thick over the city in the rainy season. The high probability of roof collapse in case of modest eruptions, such as the mid-15th-century event, combined with rainfall may press decision-makers to undertake roof retrofitting and include risk policy in urban planning.

2) Titan2F, VolcFlow, and FLO-2D models helped delineate and forecast the potentially dangerous inundation and overbank areas from a set of HCFs and DFs with flow volumes from 1.5 to 5×10^5 m^3 based on a database of flow events over the past 105 years and on historical lahars.
3) Simulated flow paths, extents, flow depths, and velocities range between values of recent flows and older events described in the literature. Impacts are measured by estimating the dynamic pressure of the simulated flows, which differ from code to code. Substantial damage would include vulnerable buildings near the channel in highly populated suburbs along drainage basins. Buildings of classes A0 and A with brick walls would be severely damaged by HCFs, particularly with flow rates below 100 m^3/s.
4) Loss fraction of buildings would be 30% in case of HCFs with 5- to 10-year return period discharges, and the proportion would increase to 100% of the lowest-quality houses hosting the most vulnerable inhabitants near the ravine channels. The cost of reconstruction and retrofitting, which would be necessary for all class A0 buildings and a sizeable proportion of class A buildings, may be unbearable for the local population. This requires attention from the civil authorities at both regional and national levels.
5) Results are potentially usable for urban planning in Arequipa. Applying the proposed methodology for assessing impacts due to HCFs and DFs is useful to understand the extent of mass-flow impacts during significant rainstorm events and develop emergency plans. This, in turn, helps raise awareness among local inhabitants and helps stakeholders formulate adequate disaster management policies in Peru or Latin American cities exhibiting similar disaster-prone conditions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

EA: field surveys, simulations using numerical code Titan2F and VolcFlow, and writing. J-CT: research project design, data collection, field surveys, and writing 50%. AG: field surveys, roof vulnerability, and writing. DR: field surveys and numerical code Titan2F. SC: simulations using numerical code FLO-2D and writing. KK: simulations using numerical code VolcFlow. GC: field survey and Titan2F training for co-authors. OS: GIS and mapping.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.865989/full#supplementary-material

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Landslide risk reduction through close partnership between research, industry, and public entities in Norway: Pilots and case studies

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Cross-sectorial and cross-disciplinary collaboration, as well as public-private partnerships are necessary to handle the complexity of climate adaptation. The Research Council of Norway has established the Centres for Research-based Innovation (CRI) in which research- and education organizations, public entities and private enterprises join forces in 8-year long collaborations. CRI-Klima 2050 focuses on climate adaptation of buildings and infrastructure and runs several pilot projects to innovate new solutions for building resilience, stormwater- and landslide risk management. Several of the major infrastructure owners in Norway are partners in the centre. Norway is increasingly affected by precipitation triggered landslides. Klima 2050 pilot projects on landslide risk reduction include a web-based toolbox for prioritizing and choosing optimal mitigation measures, including Nature-Based Solutions, improved early warning systems and mitigation measures for slope instability, and improved local warning for hazardous weather systems, all developed in close collaboration between centre partners from different sectors and disciplines. The results of these projects can all be upscaled and are transferable to other infrastructure elements.

KEYWORDS

landslides, Norway, pilot projects, cross-disciplinary, cross-sectorial, public-private partnership

Introduction

Climate change enforces needs for adapting society both in terms of scientific and engineering knowledge, but also in terms of management and governance. The complexity of these challenges requires broad, multidisciplinary solutions, harnessing the capabilities of a diverse range of organisations and institutions. Klima 2050 is a research centre focusing on risk reduction through climate adaptation of buildings and

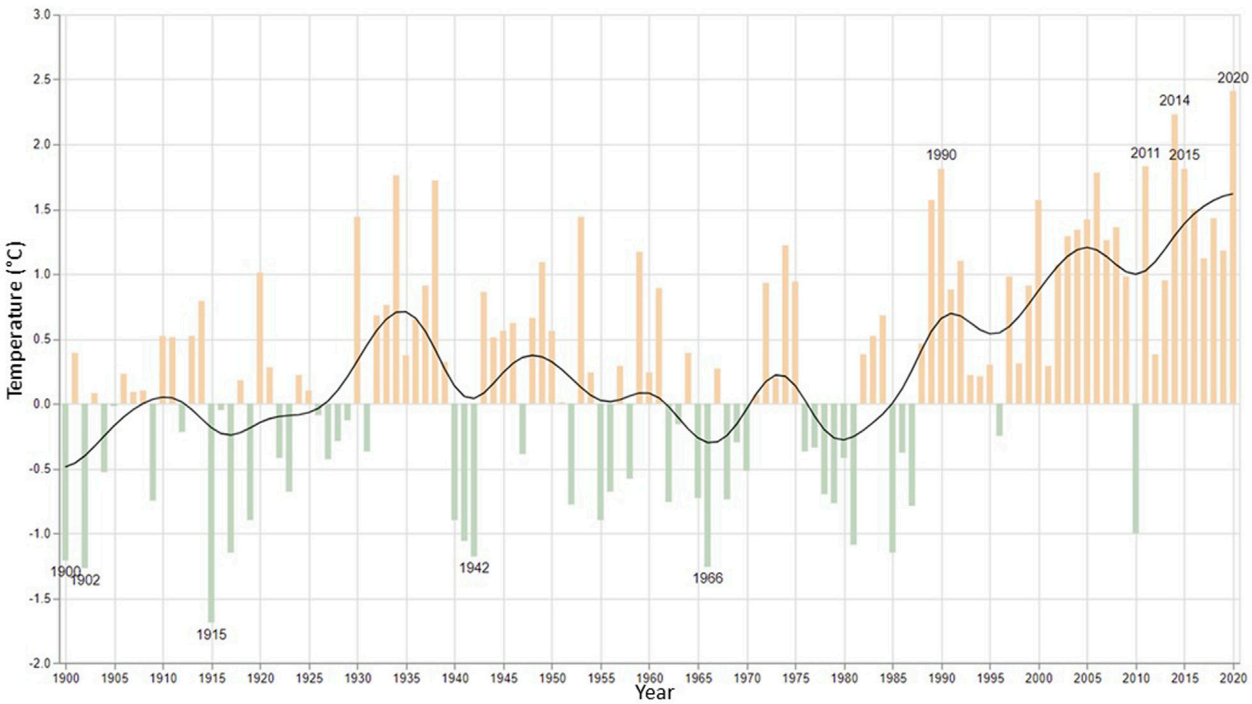

FIGURE 1
Temperature deviations from the 1961–1990 normal, from 1900 to 2020. Figures using the new normal, 1991–2020 are not available yet, but will show the same trend (Met.no).

infrastructure, where cooperation across sectors and disciplines, and the premise of active collaboration between research organisations, public entities, and commercial companies are fundamental premises to deliver on these ambitions.

Klima 2050 is funded by the Norwegian Research Council (RCN) under the instrument "Norwegian Centres for Research Based Innovation" (CRI). The CRI instrument carries funding for a period of 8 years, providing continuity and the opportunity to address deeper, more complex challenges. RCN has financed the CRI 'Klima 2050′ specifically to focus on risk reduction through climate adaptation of buildings and infrastructure.

The purpose of this paper is to present the pilots and case studies implemented in Klima 2050 to promote research addressing landslide challenges. Landslide occurrences have a close link to precipitation, and thereby climate and climate change are important drivers for landslide hazards and risk. This is a topic of great interest in Norway and Europe, it is also broadly studied internationally. The largest EU funded landslide project to date was SafeLand, a research project funded through the 7th framework program between 2009 and 2012 (Nadim et al., 2014). Moore and McInnes (2016) presented a global perspective on the nature, scale and impact of landslides on the society in the context of climate change.

A number of studies assess the connection between precipitation and landslide activity (e.g., Dikau and Schrott, 1999; Jaedicke et al., 2014; Gariano and Guzetti, 2016; Tichavsky et al., 2019). Andersson-Sköld et al. (2013) point at the need for improved documentation and active communication between different stakeholders for more effective landslide risk management. Alcántara-Ayala et al. (2017) point at main future challenges for the integration of science into local, national, regional and international policy development for Landslide Disaster Risk Reduction within the Sendai Framework. Despite numerous studies on the connections between climate and landslide risk and the need for cross-disciplinary and cross-sectoral cooperation to turn science results into action, few national collaboration programmes between research, public entities and private businesses exist.

Changing climate is evidenced in Norway through meteorological data, for example temperature. The average air temperature in Norway has increased by more than 1°C since 1900, and precipitation has increased by 18% over the same period (Hanssen-Bauer et al., 2015) (Figures 1, 2). The trends are expected to continue through this century. It is estimated that the annual mean temperature will rise by between 2.8 and 5.0°C by the end of this century relative to the reference period 1971–2000, depending on the emission scenario (RCP4.5–RCP 8.5). The equivalent numbers for precipitation are 10%–18% for average values (Norwegian Climate Service Centre, 2021).

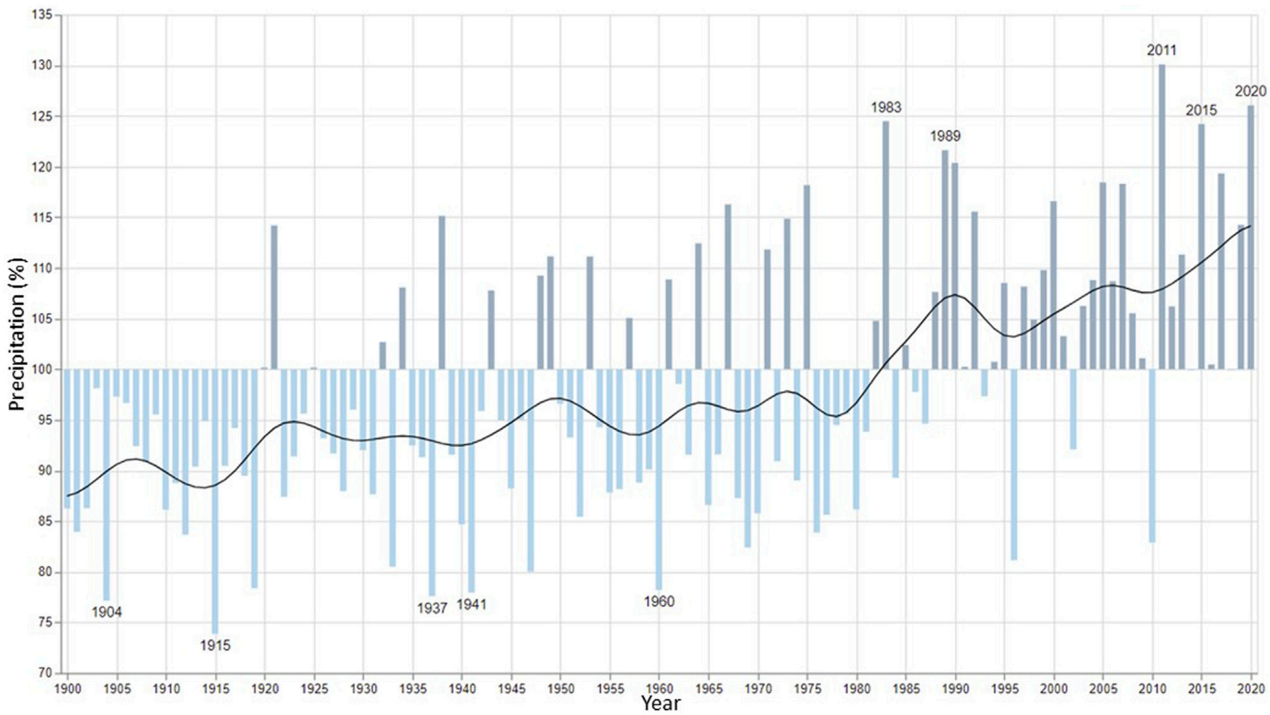

FIGURE 2
Precipitation in % of the 1961–1990 normal, from 1900 to 2020. Figures using the new normal, 1991–2020 are not available yet, but will show the same trend (Met.no).

Precipitation (rainfall and snow storage) are significant factors affecting landslide risk. Norway is already experiencing increases in both the frequency and intensity of extreme precipitation events (Hanssen-Bauer et al., 2015), leading to increased frequency of precipitation-triggered landslides and debris flows. In addition, the increase in precipitation leads to increased flooding and erosion in watercourses and may also trigger rockfall and rockslides. Considering the time lag in reversing the effects of climate change, and a life expectancy of 40 to more than 100 years for buildings and other infrastructure, adaptation to climate change within the built environment to accommodate the changing risk is inevitable (Lisø, 2006; Norwegian Government, 2010).

There are numerous challenges within climate change adaptation, and coping with these problems opens opportunities for research leading to improvements of methods and strategies as well as innovations in solutions and technology. As the challenges are multifaceted, it follows that the best solutions are likely resulting from multidisciplinary and multisector cooperation.

This paper presents the Klima 2050 research centre's implementation of pilots and case studies to address various methods, tools and strategies for addressing climate induced landslide hazards. A key aspect of these is the interaction of public, private and research organisations as a specific strategy to develop and operate the pilots and case studies. In this paper, with focus on climate induced landslides, we present 1) the context for our activities (the Klima2050 centre and landslide management in Norway); 2) the methodology for establishing cases and pilots within the Klima2050 centre, and 3) the results of these activities focusing on one case (tool development) and three pilots (field sites for research and development). We use the presented pilots and case site to describe and discuss how cross-sectorial- and disciplinary cooperation in the CRIs are used to improve climate adaptation, as well as testing out practical application of adaptation measures and strategies.

Context

Klima 2050: A collaborative project to reduce meteorological risk and societal exposure

The CRI system is based on the premise of cooperation between research organisations and user organisations, where the user organisations consist of a mix of public entities and the

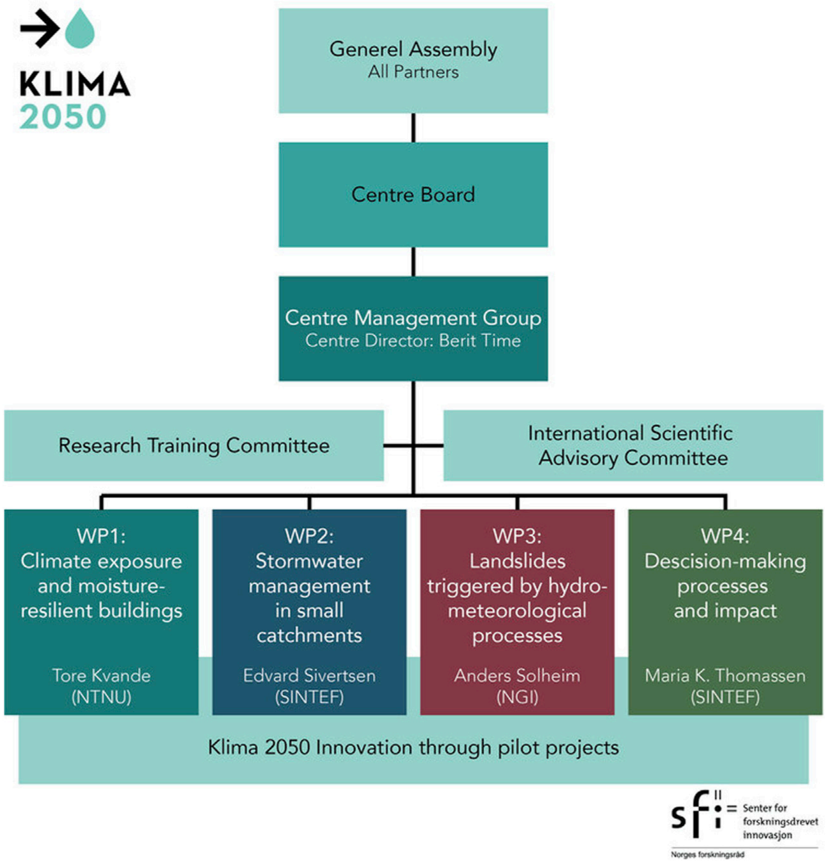

FIGURE 3
Organization of Klima 2050. Funding by the Norwegian Research Council under the CRI (SFI) instrument.

private sector companies. Experience has proved that this is a successful arena for establishing and nourishing cooperation between these diverse types of organisations. (Damvad Analytics, 2018). The "User" partners have a strong role in the CRIs: the funding scheme mandates that these partners have the majority in the centre boards, and there are specific requirements regulating the proportions of user partners and research partners in the CRIs. In addition to performing excellent research, the CRIs are expected to have a strong applied focus and innovations in methods, products and services is the key aspect of the centres. The User partners are the intended recipients of the research products. In total 59 CRIs have been funded, within a wide range of disciplines (RCN, 2021).

The system builds on experiences from similar initiatives in various countries, although none are exactly similar in length, organization, themes and organization. The US Engineering Research Centres (https://www.nsf.gov/eng/eec/erc.jsp) started as early as 1985, and has funded 75 centres in different engineering-related fields. Most relevant are probably the centres in Sweden (VINN Excellence; Stern et al., 2013), Austria (COMET; Austrian Research Promotion Agency, 2016) and United Kingdom (Catapult; Hauser, 2014). These centres are comparable in having various mixes of private and public partners and funding schemes. The centres established under these schemes differ somewhat in their sectorial focus (public, business, etc.), their service focus and their organizational model (Stahlecker, 2015; Damvad Analytics, 2018).

Klima 2050 is funded under the CRI scheme from 2015 through 2022 and consists of 19 partners including research institutes and universities 5), public entities 6) and private sector companies 8). The funding of Klima 2050 comes from RCN (43%) and the partners (57%), with the latter as a combination of cash and in-kind contributions. The centre reports to the RCN annually and all CRIs must pass a mid-term evaluation to secure funding for the full 8 years period.

Klima 2050 is organized in a structure with 4 work packages, a management group, an international scientific advisory committee, and a board of directors (Figure 3). As shown in the figure, pilot projects form the main arena for innovation in Klima 2050 and is the underlying operational structure for applied research. The scientific advisory committee is specifically included in the centre to help ensure the relevance of the Klima2050 activities in an international perspective.

Landslide hazards in Norway

Most landslide events in Norway are triggered by precipitation, mostly as rain but sometimes also in combination with snowmelt (Krøgli et al., 2018; Bondevik and Sorteberg, 2020; Schilirio et al., 2021). There are many recent examples, but two cases are particularly illustrative: the Kvam and Jølster communities. The village of Kvam in Gudbrandsdalen, south-east Norway, was hit by extreme precipitation combined with snowmelt in the spring of both 2011 and 2013. Flooding combined with large volumes of debris from nearly 100 landslides into the river flowing through Kvam led to massive damage to housing areas and infrastructure, including closure of one of the main highways through Norway, European Road E6, as well as evacuation of hundreds of people. Estimated total damages cost is more than 200 mill. Euros (Mäki et al., 2015; Devoli et al., 2018; Schilirio et al., 2021). On 30 July 2019, local high intensity rain released more than 50 landslides in the Jølster community in western Norway (Rouault et al., 2020), causing one death, disruption of roads and other infrastructure and large economic losses. These landslides were largely unexpected because the intensity of the very localized event was not detected by the forecasting systems (Agersten et al., 2019; Villa, 2021).

The direct and indirect cost related to such incidents are large. During the last 10 years, landslides and snow avalanches comprised 6% of the events reported to the Norwegian Natural Perils Pool (a joint insurance scheme), with insured losses of roughly 180 mill Euros (Finance Norway, 2021). This figure represents only the material damage to buildings. Other forms of damage, for example to transport infrastructure, farmland, power- and communication lines, as well as environmental damage, come in addition, and add largely to the total cost. Indirect costs, for example due to delays or blockages of major transport routes can be significant if the downtime is long and increase the total cost further. In the largely rural and difficult terrain of Norway, alternative routes are often significantly slower or in some cases do not exist. Social consequences, such as fear among the population, are difficult to estimate but certainly come with a cost. Proper adaptation measures, despite often being expensive to establish, may have a high cost saving potential when viewed over multi-decadal life spans.

A recent report estimated the cost of mitigating landslide and flood hazards at approximately 8.5 billion Euros for all Norwegian buildings (except vacation homes) (NVE, 2021). The estimates were based on experiences from the last couple of decades and considered therefore only “traditional” mitigation measures. This has triggered a debate on several aspects of climate adaptation in Norway, including the need for new and innovative solutions, as well as the potential benefit of closer cooperation between research, public and private entities on climate adaptation. As important as closer collaboration between different entities, is the collaboration between different scientific disciplines. A holistic approach is needed to meet the challenges posed by climate change, and relevant scientific disciplines need to avoid “silo thinking” and develop better collaboration models and practices.

Norwegian policies and strategies for landslide risk management

The Norwegian Planning and Building Act (NPBA) requires risk assessment of natural hazards for all planning and construction activity in Norway. The purpose is to give the municipality the opportunity to direct new development to areas that are less prone to natural hazards or to implement risk mitigation measures in advance. Land use planning is central to preventing adverse consequences from floods and landslides. The level of risk acceptance for buildings is defined in the NPBA based on return periods, stating that for most family homes the annual probability of being affected by a landslide should not exceed 1/1,000. For secondary buildings (storage sheds, barns, garages, etc.) the corresponding return period is 100 years, whereas for larger buildings, apartment buildings, hotels, etc., housing more than 25 people, it is 5,000 years. Similar principles apply for roads, where the allowed return periods of landslides depend on the traffic density. For railways there currently are no defined minimum return periods for natural hazards, although general risk acceptance criteria exist as a general requirement for all hazard types.

Landslide problems are managed by different sectors in Norway. The National Public Roads Authority (NPRA) is responsible for landslide problems along roads; the state railway company, BaneNor is responsible for reducing landslide risk for railways, and the Norwegian Energy and Water Resources Directorate (NVE) manages landslide risk to houses and provides assistance to municipalities and the society in general with hazard mapping, mitigation measures, monitoring and early warning, as well as assistance in case of landslide events. All these entities are partners in CRI-Klima 2050.

The Norwegian Civil Protection Act assigns responsibility to the municipalities for the safety of their inhabitants, and as such the municipalities are crucial in managing landslide risk locally. Norwegian municipalities vary widely in size, and the smallest municipalities have populations of less than 1,000 inhabitants. This consequently results in a large span in competence and available resources to deal with landslide risk at the municipality level. There is a great need for guidelines and tools to support the municipalities in making good decisions, for example, in land use planning, where the planners must comply with the requirements in the Planning and Building Act. Equally important are economy and resource planning, where the municipalities must define and prioritize mitigation measures, often within limited economic means.

An important finding from Klima 2050 is that Norwegian municipalities have access to a wealth of guidelines and websites (74 and 10, respectively) for climate adaptation (Lappegard Hauge et al., 2016). We also experience that the municipalities react differently to the regional landslide hazard forecasts issued by NVE. Consistent guidance on active use of regional landslide forecasts to improve the municipal preparedness and thereby reducing the risk to the population is therefore needed. One of the products from Klima 2050 is a new set of such guidelines for use at the municipal level (Devoli et al., 2022).

The Norwegian legislation specifies requirements for safety against natural disasters for new buildings and imposes responsibility on the municipalities for the safety of the inhabitants. Implementation of physical mitigation measures is a common way to reduce the landslide risk. However, the legislation does not specify which measures to be applied in different situations, decisions which requires competence and experience which the problem owners often do not have. For example, selecting the most suitable measure requires considering site-specific geological and geotechnical conditions, local resources, socio-economic constraints, and environmental considerations.

For linear transport infrastructure, cost-effective mitigation strategy is often to establish early warning systems combined with restrictions for users or closure of the transportation line when the hazard is too high. One of several challenges is that traditional early warning systems depend on precise weather forecasts, particularly in forecasting torrential rain, which can be very local. Another main challenge is to establish plausible warning criteria, to minimise the issuing of false alarms and to avoid missed alarms. Physical models form the basis for establishing local early warning criteria. However, the use and calibration of such models has been very limited in Norway. There is a lack of data for calibration of models, i.e. data on landslide events, where the input parameters to the physical models are known.

Materials and methods

An essential activity in Klima2050 is the implementation of pilot projects and case studies to develop innovations and solutions to overcome identified challenges. Within the landslide work package (WP3), pilots have been established to address aspects of the challenges described in the Context section:

- A tool for better and more efficient process for choosing physical mitigation measures
- A new early warning model that uses more reliable warning of torrential rain
- A calibrated physical model for landslide release
- Verification of new types of mitigation measures

The method for planning and implementing a pilot is a well-defined process in Klima 2050. Several essential criteria are in place regarding type, ownership/responsibility, and purpose. The first is that the pilot must be a natural focal point for activity, for example a physical site, a building, a large infrastructure, or a digital infrastructure such as a database. Second, the pilot must be implemented as a partnership between the three categories of centre participants, with one or more participants from each: private company, public entity, and research organisation. Third, the pilot must have an "owner", a lead partner with a specific interest in the research results arising from the pilot.

The activities implemented at the pilot shall focus on innovation, that is the development or testing of new methods, processes and tools, or adapting existing solutions to new application areas. Innovation is both a *process* and a *product*: the process is the value chain (Dwyer, 2020) from a fundamental research idea to a commercial service or product (Hansen and Birkinshaw, 2007; Roper et al., 2008), and the product is the strategic implementation of the value chain as improved products, services, methods, or knowledge and creating value for the user (Dogan, 2017). In Klima 2050, the pilots themselves are not the innovation, rather they are "sandboxes" for developing and testing innovative solutions and methods. These may be new innovations unique to Norway or represent the adaptation of existing international solutions and methods to Norwegian conditions.

To implement a pilot, an initiative is taken within one of the work packages to develop an initial concept for a pilot. Participation is negotiated with relevant partners, and together these partners develop a complete concept including site/location/infrastructure description, research and innovation objectives, implementation plan and financing plan. This concept is delivered as a proposal to the centre's management team, which based on the merits of the proposal forwards this to the Centre Board for approval. Once the pilot is formally approved, planned budgets allocated to the relevant work package may be directed towards establishing the pilot's activities.

Results

The discussion in this results section focus on four on-going pilot projects in WP3, "Landslides triggered by hydrometeorological processes" (Figure 3). These range from local to regional in scale and focus on different strategies to reduce the risk from landslides, from physical mitigation measures to improved early warning. We consider all to have considerable upscaling potential.

Landslide Risk Mitigation Toolbox: A tool for local and regional planners

Assessing landslide risk is a specialised task, often within the jurisdiction and responsibility of municipalities, however the specialised competency and experience needed is often unavailable within the municipalities' staff. While assessing risk is a difficult task, an even larger challenge is to assess the most appropriate mitigation measures, particularly considering the transition to a more sustainable society and the implementation of methods supporting this. Nature Based Solutions (NBS) form a whole new suite of mitigation approaches, in which holistic and long-term thinking are key elements. Such new approaches are often not considered, or met with scepticism, due to lack of experience and competence (Solheim et al., 2021), a deficit which is also seen in the construction business, among those who build the physical mitigation measures.

These challenges are an important motivation for developing new guidelines, methods, and tools, such as the Landslide Risk Mitigation Toolbox (LaRiMiT) web portal (www.larimit.com) (Uzielli et al., 2017; Capobianco et al., 2022) to assist planners and others, from public entities at all levels to private businesses, in their work on risk reduction. The idea for LaRiMiT started in the EU FP7 project SafeLand (https://cordis.europa.eu/project/id/226479/reporting) and has been under development in Klima 2050 since 2016.

The LaRiMiT pilot is organized by NGI, which is one of the research partners. Significant assistance during the development has been provided by several other Klima 2050 partners, in particular major government agencies, such as the Norwegian Railway Directorate, the Norwegian Energy and Water Resources Directorate and the Norwegian Public Roads Administration. Private partners have contributed with technology and experience represented in the technical solutions described in LaRiMiT. The tool was launched as a web service in 2018, and is now gaining national and international interest, both from academia and from practicing engineers both in public entities and in private businesses, such as consultants.

The LaRiMiT pilot is a web tool and corresponding database, providing a technical service for problem owners such as municipalities and infrastructure owners. Often these do not have the competence to tailor mitigation measures to the relevant hazard and addressing other factors such as cost and a host of local considerations. For example, selecting the most suitable measure requires considering site-specific geological and geotechnical conditions, local resources, socio-economic constraints, and environmental considerations. Through the LaRiMiT web-portal a user can define a problem site, and then identify, rank and select mitigation measures from an extensive database of landslide risk mitigation solutions, based on user-input attributes of site-specific slope movements and on expert scoring of the suitability of various mitigation solutions.

Inputs to LaRiMiT are provided by both users and experts (Figure 4), where user inputs define the problem, and the expert input defines the possible mitigation solutions and applicability of these. The algorithm integrating the inputs from these two groups and producing this assessment is the largest innovation in this pilot.

User inputs are on a case-by-case basis and include case-specific information defining the problem, for example: landslide type, site conditions, and the expected relevance of potential negative consequences and constraints (physical, ecological, economic, societal, environmental) brought by any mitigation measure or action for the specific case under investigation.

The experts' input is a system input, applicable for all potential cases defined by users. The experts are from both academia and the private sector, and their input is used to define the relevance, applicability, and suitability of various mitigation measures. In this process we have been particularly focused on obtaining input from private consultancies. Expert inputs include sets of candidate mitigation measures and actions, and scores for each candidate. measure with respect to a set of ranking criteria.

The database initially included only conventional (grey) solutions relying on traditional engineering methods, but the database and toolbox have been recently expanded to include Nature Based Solutions (NBS), which are sustainable techniques for managing erosion and mitigating shallow landslides using vegetation and other natural materials, copying natural processes to the extent possible (European Commission, 2015). In addition to increased resilience regarding the landslide risk, other co-benefits, such as increased biodiversity, inhabitants' well-being, aesthetics, local economy, etc. are highly valued effects of such solutions. NBS and conventional solutions can also be combined in hybrid solutions.

Following an evaluation of the website performed by Lappegard Hauge et al. (2019) improvements have been made in user friendliness, and thus effectiveness of the tool, which is open and available on-line. The website also comprises much information and examples of the various measures.

The Trollstigen pilot: Improved early warning of extreme precipitation

The Trollstigen Road in Western Norway is a scenic masterpiece of road engineering and is an extremely popular tourist destination. Unfortunately, the road is also susceptible to snow avalanches, shallow landslides, rock falls and debris flows. The investment in Trollstigen as a tourist destination will

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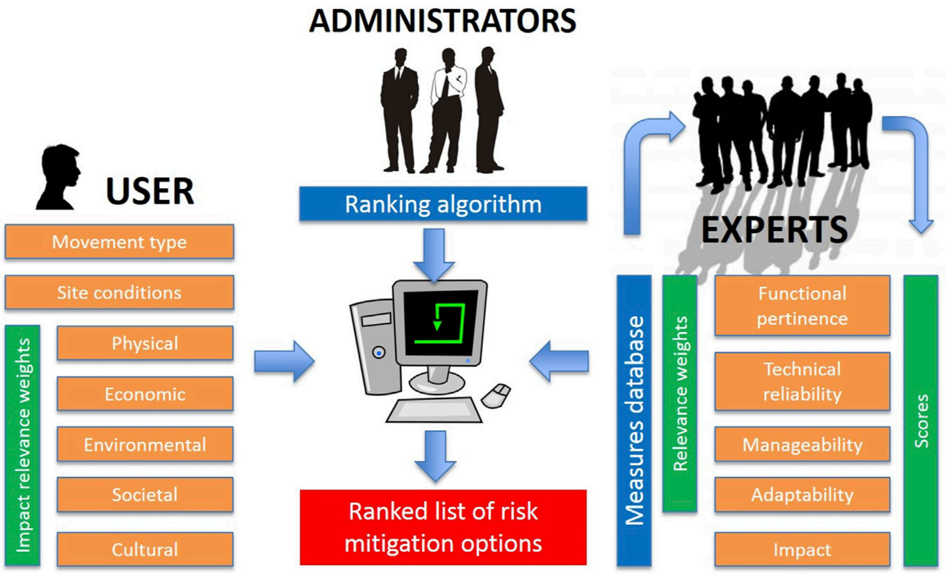

FIGURE 4
Schematic representation of the synergy between administrators, experts and users in the compilation and utilization of the LaRiMiT toolbox.

FIGURE 5
View of the road at Trollstigen and out the Isterdalen Valley (Photo: JS).

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probably contribute to the traffic volume persisting or increasing, which means that the natural hazard risks will persist or increase in the future.

The road is seasonally closed during winter, alleviating the avalanche risk for persons, but during the summer months a combination of structural measures such as netting, rock bolting and water diversion, together with periodic road closures during episodes of excessive precipitation are necessary to maintain safety. Although road closures are an effective mitigation of risk to persons and vehicles, these periods need to be limited to when it is needed and warranted, as unnecessary road closures are harmful to tourism and inconvenient for residents.

The Trollstigen pilot was established to enable research and innovation activities to develop a framework for an early-warning system integrating regional and local weather data enabling optimal management of risk using road closure as a mitigation measure. By local weather data we mean measurements at or above the Isterdalen Valley, Trollstigen road and the plateau above (Figure 5).

The pilot is a cooperation between several Klima 2050 partners, including the National Public Road Authority (NPRA), The Meteorological Institute (MET), Norwegian Geotechnical Institute (NGI) and Multiconsult Ltd. Although the local county authorities own and operate the road, the NPRA is the owner of the Pilot and represents local county interests in the project. MET and NGI bring in meteorological and geotechnical research capacity, while the private company Multiconsult represents the practicing engineering community seeking tools and solutions to implement in projects.

The pilot infrastructure includes a permanent weather station installed on the plateau providing typical meteorological measurements (precipitation, wind speed, temperature, etc.), a mobile weather radar measuring weather systems just above the plateau. Eventually, local surface water run-off measurements will be deployed at key locations in the streams and rivers in the area. In addition, extensive background data are being collected including ground and aerial lidar data and detailed photographic imaging.

Multi-disciplinary collaboration is necessary to piece together meteorological data interpretation, now-casting of changing weather, impacts of short term and highly local precipitation on triggering of geohazards, and bring this knowledge together in practical tools that consulting engineers and contractors can implement as practical installations. This integration of meteorological data at this scale (single slope) is new in Norway, and the techniques developed will be an innovation.

The expected outcome of the research at the pilot is an improved systematic approach for evaluating local weather risks on susceptible stretches of infrastructure such as roads and railways. This approach may include recommendations for permanent monitoring systems. The benefit for society is clear: improving the ability to keep roads and railways open while maintaining an acceptable risk level for users of the infrastructure. The results from this pilot can be easily upscaled by implementing similar solutions at any other infrastructure facing weather related risks.

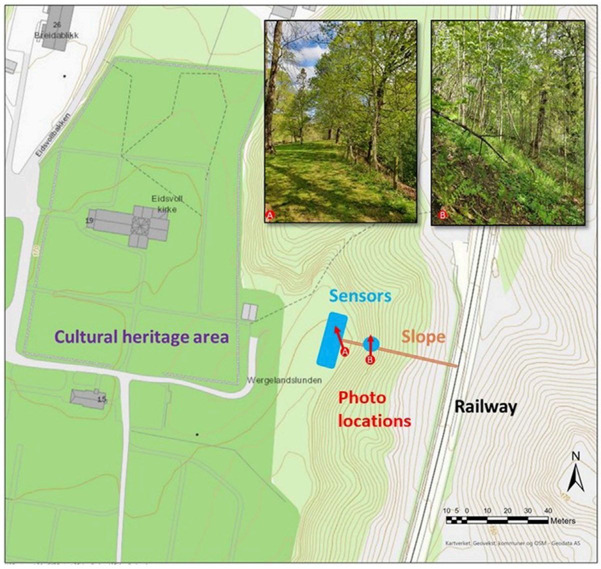

FIGURE 6
The pilot site at Eidsvoll, central south Norway. Slope, sensors, and railway location. Eidsvoll church (kirke) and the cemetery surrounding it are protected. Photos illustrate the vegetation conditions at the site.

The Eidsvoll pilot: Early warning as an effective mitigation measure

A main Norwegian railroad passes by a national heritage site consisting of a 12th century church and cemetery in the municipality of Eidsvoll, Norway. The railroad passes by the eastern part of this area, at a much lower level in the terrain. The slope from the railway up to the heritage site is about 25–30 m hight, with an inclination of about 45° in the upper part (Heyerdahl et al., 2018) (Figure 6). Landslides are the primary threat at this location, as these may impact the railway and may also damage the church grounds. As this is a cultural heritage site, it is not acceptable to implement structural mitigation measures that change or otherwise impact the landscape (Figure 7).

This slope has been the focus of research activities for several years, including the installation of sensors on the upper part of the slope in 2016 to measure volumetric water content, pore water pressures, ground temperatures and tilt at various depths in the soil profile. The pore pressures are measured across the transition zone between silt and clay

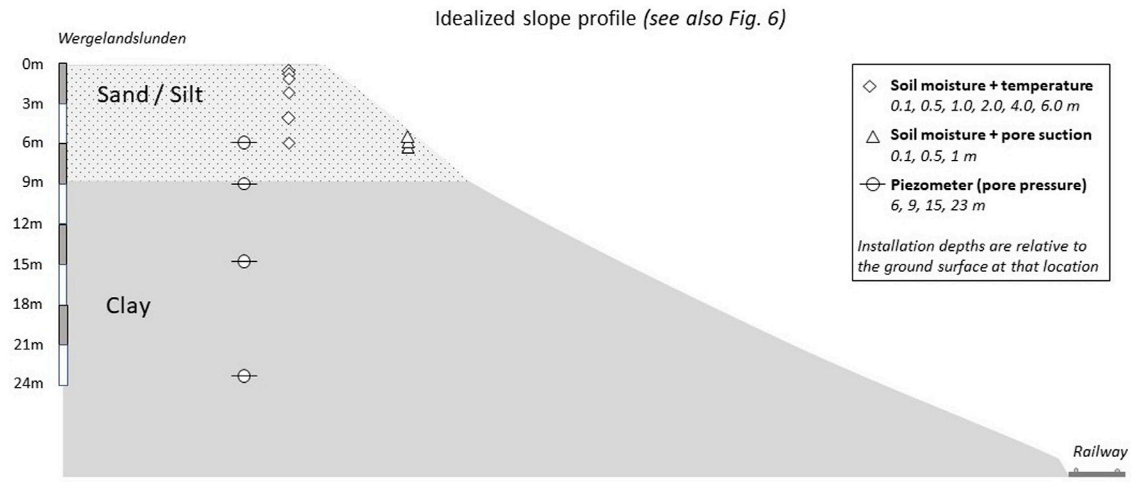

FIGURE 7
Schematic cross section of the studied slope (Figure 6) and depth location of the sensors.

layers (Figure 7). Data from these sensors is measured at 1-h intervals and the data is available real-time on a cloud-based acquisition system. In 2021, additional sensors to measure soil-water content (SWC) and soil suction were installed at several depths. These data are also available online, but via a separate cloud-based data acquisition system. Samples have also been collected for laboratory testing to determine the geotechnical characteristics of the soil including water retention curves (Heyerdahl et al., 2018).

The slope has recently been established as a Klima 2050 pilot. The main aim for this pilot project is to transform the real-time monitoring of data for rainfall and soil water conditions into an early warning system (EWS) useful to issue warnings for the road and railway authority. The pilot is initiated by the Norwegian Railway Directorate with NGI as the principal research partner At present, only these two organizations are involved, but the involvement of private organisations for the future operations of the EWS is relevant.

Currently the work is focused on defining a reliable hydrological model able to back calculate the hydrogeological variables in the slope. Further analysis will be focused on the definition of triggering thresholds to be employed in the early warning system (Piciullo et al., 2018). A slope stability software and machine learning algorithms will be employed to determine the triggering values as a function of the main input (rainfall, snowmelt, temperature, vegetation). The approach being developed for this pilot will be available for adaptation and implementation as a slope scale Landslide Early Warning System (LEWS) to forecast the occurrence of landslides and prevent fatalities and damages, and it can easily be exported to other sites nationally and internationally.

The Bodø pilot: Innovative measures to increase slope stability

Owners of linear infrastructure (roads, railways) in Norway, often face problems in long unstable slopes along their assets, particularly during periods of heavy precipitation. As there are numerous such slopes along transport infrastructure elements in Norway (and elsewhere), new, efficient, and cost-effective measures to reduce the risk related to precipitation induced slope instability are needed.

The pilot project at the Bodø railway station is located at such a slope and is implemented as a close collaboration between a public entity (the Norwegian Railway Directorate), a research institute (NGI), and private businesses (Multiconsult Ltd., Leca Ltd., and Storm Aqua Ltd.), with the Norwegian Railway Directorate as the “pilot owner.” Over the last 25 years there has been three major slope failures at the site in connection with heavy rainfall, as well as numerous smaller incidents which also have caused problems for the infrastructure at the base of the slope, such as cables, drainage and of course for the rails.

The goal of the pilot is two-fold: i) to test the methods for early warning of slope instability and/or failure of railway embankments based on instrumentation and physical stability modeling, and ii) to test and compare mitigation measures along parts of the slope, primarily in the form of various drainage measures, including Nature Based Solutions (NBS). Relatively simple instrumentation is planned for installation (Figure 8) in the form of pore pressure and soil moisture measurements, combined with a local weather station (precipitation and temperature), as well as deformation measurements along the slope, which have had several instability events. This is also closely linked to the research being carried out at the Eidsvoll

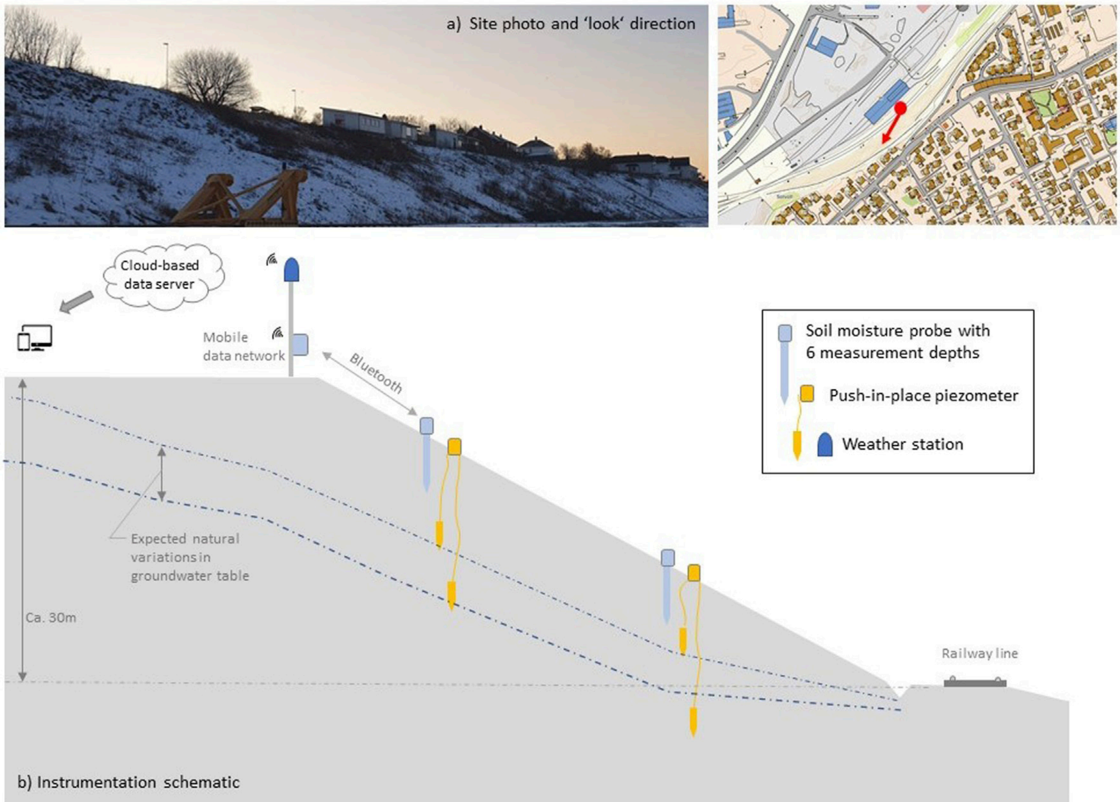

FIGURE 8
(A) Photo of the slope at Bodø station, and **(B)** schematic of the slope with installations.

pilot site (above). The sensor installations were completed in July 2022.

The available slope is a long, linear structure that is relatively homogeneous both in terms of soil conditions, geometry, and exposure. Six geotechnical borings along three profiles were carried out to define ground conditions at the site, and the installed instrumentation consisting of pore pressure measurements, soil moisture and a simple visual indicator of surficial slope movements will provide the relevant parameters needed for assessing slope stability. A local weather station is installed to monitor precipitation specifically on the slope itself, providing better data than the regional measurements would provide.

The project has defined five test plots which will allow different mitigation measures to be implemented in each plot, and the effect of these measures to be directly comparable across the five locations (Figure 9). These plots are each approximately 40 m wide with a slope height of about 12 m. Implementation of measures in these plots is still in progress.

The measures at the plots will, when complete, comprise traditional rock-filled drainage ditches, NBS (live fascines), two plots with innovative measures to be developed by two of the private industry partners, whereas one field is to be kept as per now for reference. The industry partners plan to test new field deployment designs/techniques using existing products, potentially creating a new market activity for these products. The NBS method is new in Norway, and requires adaptation using local plant species growing in Bodø. The cost and efficiency of implementation, as well as the maintenance requirements are also parameters of vital importance for the evaluation of the measures.

Discussion

An unfortunate potential pitfall in research, development and innovation is the development of information silos. An information silo is an insular knowledge system incapable of reciprocal operation with knowledge systems that are, or should be, related. As such, these systems have potential to share information with other systems but do not perform this in a satisfactorily way. Considerable localised knowledge is typically generated; but in a field characterised by information silos, information is not adequately shared but rather remains kept within each silo (Hadi et al., 2021).

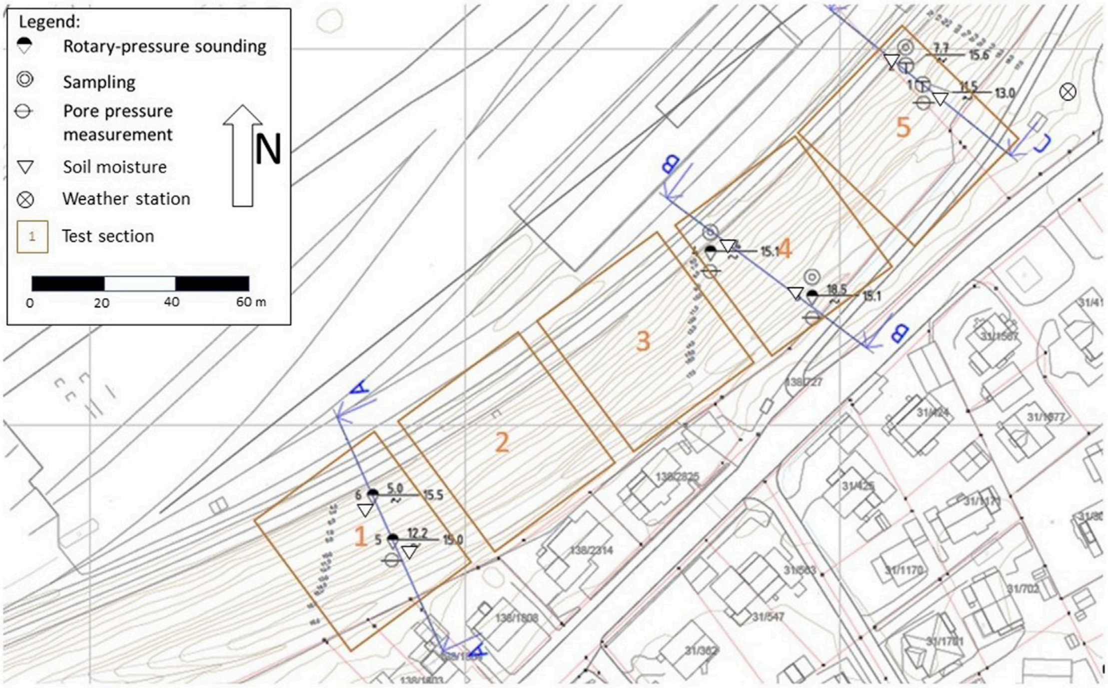

FIGURE 9
Outline of the geotechnical investigations and the five planned test fields in the slope at the Bodø Station.

However, broad collaboration between sectors and disciplines is crucial for research and innovation results that are practical and suitable for uptake and use by society. Such sharing and a holistic approach are crucial in the highly multi-disciplinary and multi-sectorial fields necessary for effective climate adaptation. The Sendai Framework for Disaster Risk Reduction (United Nations, 2015) clearly states that for all four priorities, cross-sectoral and cross-discipline collaboration are necessary, and that involvement of stakeholders at all levels is a necessity. This is further emphasized by the IPCC special report on Climate Change and land (IPCC, 2019), which also points at the importance of cross-sectorial and public-private cooperation in both climate change adaptation and mitigation.

Sectorial silo thinking was identified as one of the key barriers for implementing Nature Based Solutions (NBS) in climate adaptation work in urban areas by Kabisch et al. (2016). The same may be stated also for other new and innovative measures, where sectorial silos and scepticism to the "unknown" form main barriers. Wamsler et al. (2020) pointed out that sharing of experiences and knowledge between groups with different expertise and experiences is important for overcoming barriers. In their case this was linked to the context of NBS, but the conclusion is generally valid.

The CRI scheme is set up to mitigate these barriers, and to promote cross-sectoral collaboration. Promoting cross-sectorial cooperation through CRIs is an effective way to avoid discipline- and sectorial silos, in which ideas, data and information are not shared across scientific or sectoral boundaries. In Klima 2050, this is particularly relevant regarding climate adaptation, as several of the most important infrastructure owners are partners in the Centre. These comprise the Norwegian Public Road Administration, the National Railroad Administration, Statsbygg–the owner of all state-owned buildings in Norway, Avinor–which manages the civil airports in Norway, the Norwegian Energy and Water Resources Directorate as well as several building companies. All of these are involved in the active research of the centre, such as the pilot projects.

Klima 2050 performs much of its research in pilot projects, each of which can be considered research and demonstration projects. We have found this a fruitful way of developing and testing of new adaptation methods and strategies. The examples of pilot projects described above show how organizations within different fields and sectors (private–public–research) join forces to develop better methods and strategies. Although the pilots presented here focus on climate induced landslides, pilot projects also form important parts of the other work packages of Klima 2050. Examples include smart solutions for climate adaptation of buildings (WP1, Figure 3) made in close cooperation with the AEC industry partners of the CRI and innovative drainage solutions are made to mitigate against urban flooding (WP2, Figure 3), as well as networks for improved governance related to climate adaptation among municipalities in a county (WP4, Figure 3).

The value of joint pilot projects is also acknowledged by Frantzeskaki et al. (2019), who state that careful experimentation through demonstration projects can bring about powerful tools for codesign, and co-learning. Furthermore, demonstration projects provide opportunities for tracking the costs and benefits of actual "real" examples when they are of appropriate scale (Fink 2016). Such projects, in turn produce data and an evidence base for improved decision-making (Bulkeley et al., 2016; Voytenko et al., 2016).

Public–private partnerships (PPP) have become more common for large investments, for example in transport infrastructure in Norway. The Sendai Framework (United Nations, 2015) again points out that public and private investment in disaster risk prevention and reduction through structural and non-structural measures are essential to enhance the economic, social, health and cultural resilience of persons, communities, countries, and their assets, as well as the environment. These can be drivers of innovation, growth, and job creation. Such measures are cost-effective and instrumental to save lives, prevent and reduce losses and ensure effective recovery and rehabilitation. The RCN promotes these kinds of partnerships in the research and development activities in Norway through the strictly regulated partnerships in the CRIs. Results of the CRI activities will most likely lead to histories of successful collaboration between sectors, which, according to Chen et al. (2013) is likely to build social capital, and well-functioning partnerships.

Public - private partnerships have also been recognized as an important element by Seaberg et al., 2017) in their analyses of game theory applications in natural disaster management research. They found that game theory is used frequently to model both mitigation and disaster response. They also find that most research has been performed on disaster relief and suggest that future research should be more directed towards mitigation, preparedness, and recovery. This is well in line with Klima 2050 priorities, with its focus on preparedness and mitigation.

Concluding remarks

- The Centres for Research based Innovation (CRI) is a funding scheme which promotes cross-sectoral and cross-disciplinary collaboration. It also promotes public-private partnerships and is as such a well-suited instrument to overcome many of the barriers identified in the literature regarding climate adaptation strategies, as well as other themes, and as such provides excellent opportunities for innovation related to climate adaptation.
- CRI-Klima 2050 focuses on pilot projects, established as cooperative efforts between several of the centre partners. This is an efficient way of testing new methods and strategies and may also provide success histories which are important for export and upscaling of the innovations. While the pilots formally end with the completion of Klima 2050 in the spring 2023, it is the intention that these will continue as focus points for research, development, and innovation in continued cooperation between the Klima 2050 partners.
- Management of landslide risk is handled by several different entities in Norway, resulting in a wide range of regulations and guidelines. The municipalities have the final responsibility for the safety of their inhabitants but are often small and have limited resources, experience, and competence. Klima 2050 develops a common set of guidelines on how the municipalities should react when national landslide warnings are issued. The Centre has also released the web-based toolbox LaRiMiT to assist municipal planners and other stakeholders in choosing the optimal landslide mitigation measure, tailored to their specific problem and local physical and socio-economic conditions.
- Improved monitoring and early warning systems are being developed and tested in pilot projects at sites in different areas of Norway, representing different situations, topographic conditions, and climate. These systems aim at optimal traffic control (roads and railroads), particularly for areas where physical mitigation measures are not adequate or are impossible for various reasons. Information from sensors in the ground and remote sensing are combined in machine learning algorithms to issue precise warnings to be used by the relevant stakeholders.
- Results from the pilot projects are all relevant for upscaling and are transferable to other locations with similar challenges, in Norway as well as internationally. All data and results are also open and available for anyone, in accordance with Norwegian laws for publicly funded research.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: www.klima2050.no.

Author contributions

AS leads the Klima 2050 work package on landslides and is the lead author of the manuscript. All other co-authors have contributed equally to the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Volcanic risk management practice evolution between vulnerability and resilience: The case of Arequipa in Peru

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This paper proposes a new way of understanding the debate between vulnerability and resilience. We mobilize on the theoretical level the notion of "paradigm" in the sense of Kuhn and, on the methodological level, Foucault's notion of "apparatus" to understand volcanic risk management practices. Through an interdisciplinary approach, combining management, geography and Earth sciences, we study the evolution of volcanic risk management practice in Arequipa (Peru) from the 1990s to the present. To do this, we look at the history of volcanic risk management in Arequipa, using a qualitative interview methodology based on six in-depth centered interviews from the main actors of this history, supported by a 2-month ethnography which allowed access to large institutional documentation (reports, studies, archives, maps, pictures...). Management practices in Arequipa appear to be centered on the paradigm of vulnerability since the 1990s. Some operations since 2015 named as resilient emerge but they are still inscribed in the vulnerability paradigm. The results show the relevance of the theoretical and methodological framework chosen for Arequipa but also the possibility of using it in a more general way.

KEYWORDS
vulnerability, resilience, paradigm, risk management practice, Arequipa

Introduction

The purpose of this paper is to make a theoretical proposal to account for volcanic risk management practices through an interdisciplinary approach combining management, geography and Earth sciences. We note on the one hand a deficit of theorization around "management practices" in the field of Earth sciences (Donovan and Oppenheimer, 2014) and on the other hand a difficulty in distinguishing and articulating practices in reference to the concepts of vulnerability and resilience.

Volcanic risk management practices are associated with the notion of vulnerability and/or resilience, which are relatively intertwined and connected notions as expressed by Cutter et al. (2008). To clarify the debate, we approach the interaction between vulnerability and resilience from the notion of paradigm in the sense of Thomas Kuhn (1972), considering that within each paradigm, there is always "a point of view on the world" beyond the theoretical part. The passage from one paradigm to another paradigm is always a radical change of point of view capable of better integrating a number of questions posed by the previous paradigm. Thus, it is possible to propose a reading grid of the two paradigms by pair of contrasts. The multiplication of works on vulnerability and resilience, but also of the links between them in the field of volcanic risk management, makes a conceptual clarification necessary.

Recent studies also note the lack of literature to articulate practices in relation to vulnerability and resilience (Miller et al., 2010; Fekete et al., 2014). To answer this deficit, we refer to a new current of research in social sciences centered on practice from the seminal works of Foucault (2001; 2009), Giddens (1979), Bourdieu (1972) and Latour (2006). Based on a narrative on the history of volcanic risk management in Arequipa, we highlight local risk management practices and their arrangement in an apparatus, considered as a methodological tool. We approach the notion of "apparatus" in the sense of Foucault (2001), extended in organization and management sciences (McKinlay and Starkey, 1998; Gilbert and Raulet-Croset, 2021). We use the notion of apparatus as a methodological tool to understand management practices as a set of heterogeneous elements such as theoretical frameworks, tools, institutions, places, etc. These social and material elements are linked together in order to obtain a performance (Foucault, 2001). This way of understanding practices is close to the theory of assemblage in the geography of risk (Donovan, 2017) which is based on the work of Latour (2006).

First, we review the links between vulnerability and resilience through the notion of "paradigm" in the sense of Kuhn (1972) to clarify the transition from vulnerability to resilience. Secondly, we present the context of Arequipa and the methodology through the notion of apparatus (Foucault, 2001). In the third part, we present the factual evolution of volcanic risk management practices in Arequipa, Peru, as close as possible to the categories constructed by the stakeholders since the 1990s. In a fourth step, we test our theoretical grid to interpret this history. In a conclusion, we identify the main contributions of this work, the related limitations and future perspectives.

Risk management: From a vulnerability to a resilience paradigm

Volcanic risk management practices are associated with the notion of vulnerability and/or resilience, which are relatively related, intertwined, and connected notions as expressed by Cutter et al. (2008). To clarify, we proposed to approach the interaction between these two notions from the notion of paradigm in the sense of Kuhn, considering that within each paradigm there is always beyond the theoretical part "a point of view on the world," and that the passage from one paradigm to another paradigm is always a radical change of point of view able to better integrate a number of questions posed by the previous paradigm. Thus, it was possible to propose a reading grid of the two paradigms by pair of contrasts.

We mostly rely on the literature in geography on the concepts of vulnerability and resilience in their approach to natural or technological hazard management. This literature is very large, in terms of the number of articles published over the last 40 years (Barroca et al., 2013, see Figure 1). It is also extremely complex (Morin, 2008) in the sense that contradictory and opposing logic emerges, while links are also proposed between the literature on the two concepts (Fuchs and Thaler, 2018). As Cutter (2018:257) reminds us, "Vulnerability and resilience are well known and often discussed concepts in disaster research. Depending on the disciplinary, methodological, or philosophical perspective, these two concepts have very distinct and contested meanings and research traditions.".At the same time, many researchers propose to establish links between these two concepts (i.e. Adger, 2006; Folke, 2006; Cutter, 2006; Gallopín, 2006; Turner, 2010; Miller et al., 2010; Cutter, 2018). Some even speak of a continuum between these two approaches by suggesting "social vulnerability" as a bridge between the two (Cutter, 2006; Miller et al., 2010; Provitolo, 2010).

We approach the debate between vulnerability and resilience in geography from the notion of paradigm in the sense of Kuhn (1972): a succession of paradigms that each time constitute "a new world view," combined with a theoretical corpus, methods, emblematic cases, indicators, etc. One can understand a previous paradigm one from the point of view of a new paradigm 2, but not vice versa. Kuhn (1972) defends the idea of the relevance of paradigms in the development of science, as they allow a community to focus on a certain type of problems and solutions.

We suggest a reading of the debates between vulnerability and resilience from a paradigm point of view. Thus, we consider vulnerability as the first paradigm, which proposes to address the issue of so-called "natural" risk management and which has been constructed since the 1970s. White (1974), geographer at the University of Chicago, appeared as the precursory proponent of this approach, which was to become the dominant paradigm in the 1990s (Cutter, 1996; Dauphiné 2001; Adger, 2006). The emergence of the resilience paradigm in the 2000s can be understood as a response to the problems faced by the vulnerability paradigm. It is in this way that we interpret the work of Alexander (2013) in his etymological journey around resilience. The concept comes from ecology and psychology and challenges social science (and geographic approaches) to risk reduction by proposing a new approach. Other researchers also

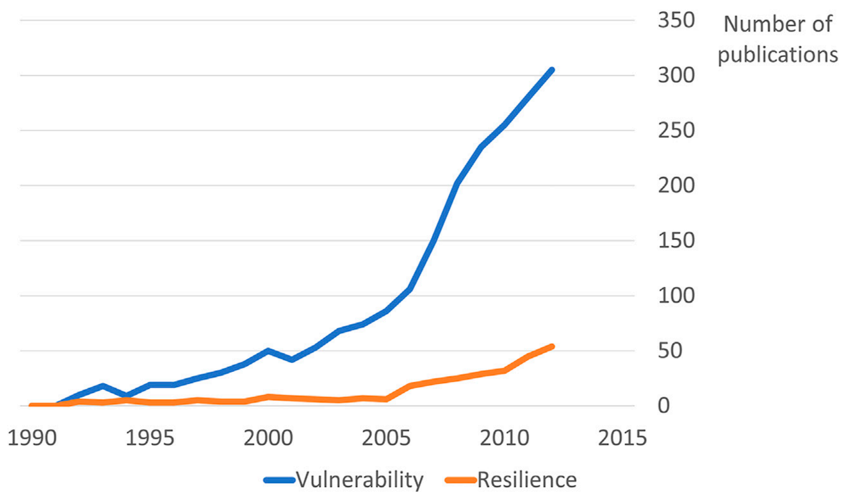

FIGURE 1
Geography publications with "vulnerability" or "resilience" in their title, based on data available on Web of Science (reproduction from Barroca et al., 2013).

considered this evolution (Dauphiné and Provitolo, 2007; Barroca et al., 2013; Tomassi, 2018). At present, both paradigms are not equally mature, and the resilience paradigm is still in an exploratory stage compared to the vulnerability paradigm, as can be seen from the quotes below:

"To reduce the damage from disasters, practitioners have for centuries proposed a strategy to improve the resistance of societies to a hazard. They calculate increasingly precise predictable magnitudes of the hazard, and then persuade officials to build defensive equipment to protect society. Following this strategy, they built dykes along rivers and then dams upstream against flooding. Anti-seismic measures are also part of this approach, effective when the precise impact of the hazard can be predicted. However, this situation is exceptional. There are many reasons why it is often impossible to obtain accurate results and therefore to properly calibrate structures. It is then possible to adopt another strategy based on the concept of resilience. This second strategy aims, not to oppose the hazard, but to reduce its impacts as much as possible." (Translated from Dauphiné and Provitolo, 2007:115–125).

"At the turn of the millennium, after having put forward the concept of vulnerability, resulting from the politicization of risk and disaster studies during the 1970s, risk management was enriched by a new notion, that of resilience. This concept has enabled us to renew the way in which we conceive the relationship between urban society and risks (natural or technological) in a context of climate change, high uncertainty and increasing number of disasters. At a time when we thought we had mastered natural hazards thanks to technology, the latter revealed its unthinkable aspects and the fragility that accompanies it. Sometimes seen as the positive side of vulnerability, resilience is an integrative notion with a fairly broad meaning that concerns not only the capacities of a social group and/or a territory (or, more broadly, a socio-technical or ecological system, etc.) to cope with a disaster, but also its ability to recover from this disruption and turn it into an "opportunity."" (Translated from Tomassi, 2018:1).

As these two extracts show, it is in the face of imprecise, or unmeasurable risk predictions that resilience emerged as another way of approaching risk management from what we must call uncertainty. An important distinction must be made between the notion of risk and that of uncertainty. Vulnerability is based on a classical vision of risk, i.e., a potential danger whose probability of occurrence can be calculated objectively and historically (Fischhoff et al., 2011). In this perspective, uncertainty is ultimately understood as risk and if objective probabilities are not possible to know, subjective probabilities will be mobilised, using the point of view of experts, making a reduced distinction or merging these two without making any logical distinction between these two categories. Taking the limitations of this approach to risk as our starting point, we will explore uncertainty in order to address the new perspective of resilience. This is a "radical uncertainty" in the sense of Knight (1921), and Callon et al. (2009) point out, that the notion of uncertainty can be understood more precisely in terms of the unknown, i.e., "the only thing we know is that we do not know." Therefore, an improvement of the overall resilience of a system is to improve its ability to cope with the unknown, i.e., with situations that cannot be anticipated. These two perspectives, a risk-based approach to vulnerability and an uncertainty-based approach to resilience, represent a radical theoretical opposition in the way risk management is

TABLE 1 The contrasts between the paradigms of vulnerability and resilience.

Paradigm	Vulnerability	Resilience
Definition	The propensity to be negatively affected by and unable to cope with potentially dangerous situations	The ability to cope with and learn from potentially dangerous situations
	It is a static state	It is a dynamic capacity
Basic principle	It is possible to technically control the impact of a hazard on a territory	The impact of a hazard can be reduced by building on the overall adaptive capacity of the territory
Approach	Analytical—Deterministic	Complex system
Starting point	Hazard	Territory
Nature of the solution	Technical Factor	Human Factor
Characterization of the approach	Defensive	Offensive
	Top-Down	Bottom-Up
Centering	Risk	Uncertainty
Problems and limitations	a) The degree of accuracy of predictions related to the impact of the hazard is still insufficient	a) The difficulty of constructing indicators to measure resilience
	b) It is difficult to incorporate the adaptive capacity of the system into the model	b) Complexity of implementation

approached. This radical opposition between risk and uncertainty has been tackled head-on by economists and sociologists such as Dupuy and Grinbaum (2005) and Callon et al. (2009).

Barroca et al. (2013) suggest presenting vulnerability and resilience as two opposing perspectives, although there is also work that tends toward the unification of the two concepts. Vulnerability is centred on a state of fragility of a territory in reference to a potential danger, from an analytical perspective, and the resilience on a capacity to cope and learn from a potential danger, from a systemic and complexity perspective. We have retained from Barroca et al. (2013) the opposition of vulnerability and resilience, employing on one hand, an analytical approach and, on the other, a systemic approach based on the work of Le Moigne (1977).

We propose to account for the debate between vulnerability and resilience paradigm as an opposition between two world views that can be radically opposed in terms of definition, basic principle, approach, starting point, nature of the solution, characterization of the approach, focus and finally in their problems and limitations.

We retain the definition proposed by Kelman et al. (2015) in their article, where they borrowed from the work of the IPCC 2013-2014. Vulnerability is, "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." We retain two basic elements 1) "a propensity to be adversely affected" by something potentially dangerous and 2) an inability to cope. This is a static state of fragility. This idea is reflected in the benchmark paper of Adger (2006): "Vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt." Resilience is defined as The capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or reorganizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation. We retain two important elements which make resilience appear the opposite of vulnerability as: 1) "the capacity (...) to cope with a potentially dangerous situation" (p. 132, Kelman et al., 2015), and 2) the ability to learn from this event. It is a dynamic capacity to learn. We propose a comparison of these two concepts below (see Table 1).

The vulnerability paradigm is based on a basic principle: it is technically possible to control the impact of a hazard on a territory. It is an analytical and deterministic approach. The starting point of the analysis is the study of the hazard and its probability of occurrence, and the ability to assess the probability of the hazard causing damage to the area. The solution is technical. It is a defensive, top-down approach, centered on a classic risk approach. This perspective poses problems of two kinds: 1) the degree of precision of the forecasts related to the impact of the hazard often appears insufficient and the reality deviates from the established scenarios, 2) it is difficult to integrate into the model the adaptive capacity of the system.

The resilience paradigm is based on a basic principle: the capacity of a territory to adapt can reduce the impact of a hazard. The starting point of the analysis is the study of the characterization of the socio-technical system that constitutes the territory. It is a complex system approach. The solution is based on the capacities of individuals, groups and the territory to deal with the actual situation. It is an offensive, bottom-up approach, centered on an approach to uncertainty (Callon et al., 2009). The problems encountered by this perspective are twofold: the difficulty of constructing indicators for measuring resilience and the complexity of implementing them.

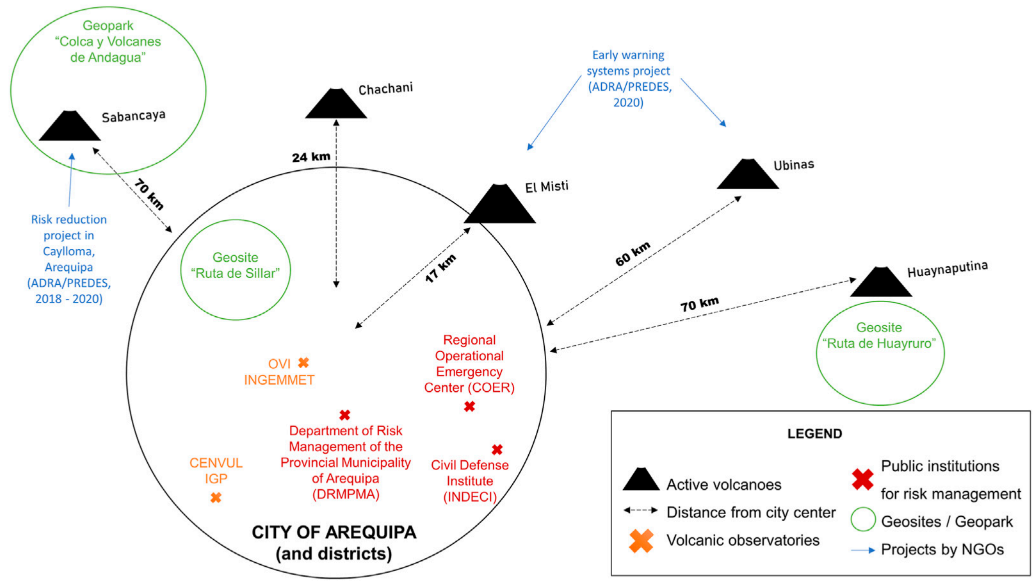

FIGURE 2
Volcanic context and risk management stakeholders in and around Arequipa.

We will continue the discussion on the relationship between the two paradigms in terms of their complementarity or their substitution with possible integration or replacement by complete rupture. As recommended by some authors (Miller et al., 2010; Fekete et al., 2014), we aim to provide a new way to link the vulnerability and resilience paradigms to their effective practices by applying them in a specific territory: the city of Arequipa in Peru.

Volcanic context in Arequipa in southern Peru

Arequipa is a city of 1.1 million inhabitants in southern Peru (INEI, 2018), with a historical centre listed as UNESCO World Heritage, and city outskirts rapidly expanding, with informal urbanization, into areas exposed to geological, seismic, and hydro-meteorological hazards. Arequipa is framed by three large volcanoes: Chachani, El Misti and Pichu Pichu. El Misti is active and constitutes a probable eruption threat for the city, Chachani is potentially active, and all three volcanoes host a major risk of torrential floods and lahars (volcanic debris flows). We illustrate the volcanic context and some risk reduction measures below (see Figure 2).

El Misti erupted last in 1440–1470 AD (Thouret et al., 1995) and has a 2000–4000-years highly hazardous Plinian eruptive cycle (Cobeñas et al., 2012). The volcano currently exhibits only slight gas plumes and is not an immediate hazard. However, the numerous ravines originating from El Misti and that cross the city of Arequipa are major features in terms of risk in Arequipa, as the city experiences destructive events related to torrential rains almost every year. The monopolization of attention on these hazards that occur annually counter-intuitively hinders risk awareness about a potential eruption, even though such events should raise attention to the lahars that would be induced in the event of a large eruption by the remobilization of freshly deposited volcanic material (Sandri et al., 2014).

Less than 75 km northwest of Arequipa, two other volcanoes are currently erupting, and have been doing so regularly for the past 30 years: the Sabancaya volcano (70 km northwest) and the Ubinas volcano (about 60 km east, in the Moquegua province). Like El Misti, they are continuously monitored by the Geophysical Institute of Peru (IGP) and the Volcanic Observatory of the Geology, Mining and Metallurgy Institute (OVI-INGEMMET). Risk management programs around volcanoes in southern Peru involve different stakeholders, such as: the Regional Operational Emergency Center (COER), the National Institute of Civil Defense (INDECI), the National Center for Disaster Risk Estimation, Prevention and Reduction (CENEPRED) and the Department of Risk Management of the Provincial Municipality of Arequipa (DRMPMA).

Since 2014, all of these stakeholders have been part of the national disaster risk management system (SINAGERD). The COER is in charge of coordinating emergency risk management at the regional level, and the INDECI relies on it to act operationally in helping the population before, during and after disasters. The DRMPMA is in charge of all the work and training to be done on the culture of risk management in its provincial territory, which includes the city of Arequipa and its districts. In this paper, we propose to document the different volcanic risk management practices in Arequipa in the last 30 years.

Methodology

We chose a qualitative methodology to approach the stakeholders' volcanic risk management practices as closely as possible *in situ* in order to document the links that unite them to vulnerability and resilience paradigms. We made a literature review on the vulnerability and resilience paradigms in geography to better understand the theoretical discussion and analyze their influence on policies and regulations in Arequipa. To approach the notion of practice theoretically, we rely on the growing body of seminal work in the contemporary social sciences around Foucault (2001), Foucault (2009); Giddens (1979), Bourdieu (1972), and Latour (2006). It is a real turning point in the field of social sciences. The book directed by Schatzki et al. (2001) constitutes an important step in this direction, it is through practices (which include actions and interactions) that we can understand the organization, reproduction and transformation of social life. This perspective has given rise to important developments in the field of management science *via* what is known as the Strategy-As-Practice (SAP) current (Whittington, 1996; Jarzabkowski, 2003; Golsorkhi et al., 2010; Fenton and Langley, 2011; Rouleau, 2013; Whittington, 2017).

To approach volcanic risk management practices, we did an ethnographic investigation in residence in the main volcanic observatories (Geophysical Institute of Peru (IGP) and the Volcanic Observatory of the Geology, Mining and Metallurgy Institute (OVI-INGEMMET) between January and March, 2020. This led to the writing of a field diary (100 pages) and six in-depth centered interviews.

For these interviews, we selected historical actors from IGP, INGEMMET, and LMV who lived the early times of the work done in Arequipa (around 1994–2002). They were anonymous and their average duration was around 50 min. We conducted our interviews with an approach centered on the historical, chronological and living experiences of the interviewees to allow them to produce a fluid discourse (Morris, 2015) while we addressed several themes during the conversation: materiality and symbolism around the volcano, volcanic risk management, political and media stakes, the way scientist and institutions are perceived, and their experience of a lived extreme event i.e., a disaster or a crisis. This method seems particularly suited to the construction of a narrative from the stories lived by the actors because it produces "a way of knowing" (Seidman, 2006).

Interviews were analyzed with a grounded theory approach (Glaser and Strauss, 2017) using a constant comparison analysis to select the different activities reported and to code them as practices. This coding allowed the emergence of indigenous categories ("risks awareness center," "volcanic eruption simulation," etc.) that represent practices developed in Arequipa. We do not pretend to list exhaustively all the practices observed in Arequipa but we highlight those that have been major steps in improving risk management. Obviously, the choices made are not of the order of establishing a hierarchy of values, but of a will to show the variety of practices in an objective synthesis.

We collected a rich documentation that have helped us to triangulate the data and chart the progression of ideas on how to deal with the negative effects of volcanic and other associated hazards (i.e., lahars, hail, snow, earthquakes). This is done by following the scientific literature specifically focused on Arequipa from the 1990s and reports from governmental bodies, such as geological surveys (IGP, OVI-INGEMMET), observatories and civil defense. Such reports are considered the main local way of science communication.

We used all this documentation to reconstruct the history through a realist narrative approach, "to put ethnography on the intellectual and literary map" as described by Van Maanen (2011) and based on the proposition for a Foucaldian approach to narratives (Tamboukou, 2008). Throughout the narrative below, we factually reference all the management practices carried out by the actors around the monitoring and management of volcanic risks in Arequipa. We follow Foucault's genealogical approach (2009) to illustrate the way these elements combine in a genealogical map and create an assemblage that fulfills a role in volcanic risk management.

Indeed, the notion of apparatus (Foucault, 2001; Foucault, 2009) is an assemblage that associates technical and social elements in the production of a performance. Management sciences have taken up this notion and adapted it for many years (McKinlay and Starkey, 1998; Gilbert and Raulet-Croset, 2021) to define a management apparatus as:

a) a set of heterogeneous elements,
b) which are linked together,
c) with the aim of producing a performance in relation to an activity.

The assemblage includes elements of different nature: stakeholders and institutions, theoretical frameworks, plans, events, projects, tools, places, etc. We will look at the practices in relation to theses elements which are crucial to developing volcanic risk management. The links between them make the performance of the system and may evolve during the history of the system. Based on these principles, two possibilities have been proposed: The Actor Network Theory (Latour, 2006) divides human and non-human actors, but we rely on the approach based on management instruments, which includes material and social elements in their assemblage (Gilbert and Raulet-Croset, 2021). This could eventually fit with the research field around

Disaster Risk Management Assemblage (DRMA), a research current that proposes to approach Disaster Risk Management (DRM) from an assembly theory (Grove, 2013; Angell, 2014; Grove and Adey, 2015; Gillard et al., 2016; Donovan, 2017; Marks, 2019; McGowran and Donovan, 2021).

This methodology allows us to analyze practices around volcanic risk management in Arequipa and discuss them in relation to the vulnerability and resilience paradigm. This could eventually help stakeholders to review their experience around volcanic risk assessment and management in Arequipa from a reflective, historical and social perspective, as recommended by Gaillard (2010) to move away from a technocratic vision of disasters.

1994—2020: History of volcanic monitoring and risk management in Arequipa, Peru

In the early 1990s, little was known about the eruptive potential of the volcanoes of southern Peru, although this area was considered one of the most dangerous in the world, also facing seismic and meteorological hazards (De Silva and Francis, 1991). Despite a series of studies conducted by a few researchers before the 1990s (Bullard, 1962; Hoempler, 1962; Gonzalez Ferran, 1990; Huaman-Rodrigo et al., 1993), volcanic monitoring was still in its infancy and risk management was almost very limited, but IGP started the volcanic monitoring of Sabancaya volcano between 1988 and 1994. A study conducted locally in Arequipa at the University of San Agustin (UNSA) provided the first basis of knowledge about the potential hazards of El Misti (Macedo, 1994; Masuno Kosaka et al., 2000). The arrival of Jean Claude Thouret (IRD) in 1995 (Thouret et al., 1995) in Arequipa started the first hazard assessment studies of the volcanoes: Ubinas, Huaynaputina, Ticsani, Misti, and the training of several volcanologists.

At the beginning of the 2000s, Peru was largely under-resourced in terms of human and organizational resources to deal with natural hazards, especially in southern Peru. The institutions such as INGEMMET and IGP, which operate volcano mapping and monitoring, were based in Lima and had no local Arequipa branch. The IGP installed a volcanology office in Arequipa in 1988, due to the reactivation of the Sabancaya volcano which continues to present. IGP thus began a temporary monitoring of volcanoes that developed slowly until 2004. Over this period, a telemetric seismic network was installed at El Misti in partnership with the French Institute for Development (IRD), and the Regional Government of Arequipa. The volcanoes gradually began to have monitoring equipment installed with help from foreign donations (such as from the USGS), but between the years 2000 and 2010, some of the institutions had great financial difficulties, preventing the development of their activities.

The geographers Degg and Chester (2005) proposed an initial history of this research, noting that there have been two major research agendas around vulnerability in Peru, and particularly in Arequipa: a first focused on physical factors related to vulnerability, and a second more integrated approach, led by Jean-Claude Thouret, aimed at considering the social factors in urban areas related to risk. A first agenda of research has helped to clarify the eruptive processes and hazards of different volcanoes in the region such as Sabancaya which erupted in 1990 (Thouret et al., 1994), and Huaynaputina which had a massive eruption in February 1600 AD (Juvigné et al., 1997), Ubinas volcano (Thouret et al., 2005) and El Misti volcano (Thouret et al., 1995; Thouret et al., 2001), which also erupted around 1440–1470 AD. Jean-Claude Thouret was primarily preoccupied with El Misti, since it looms over the city of Arequipa, threatening nearly one million inhabitants (as of 2001). He, therefore, introduced the second agenda of social vulnerability with Robert d'Ercole (D'Ercole et al., 1994; Thouret and D'Ercole, 1996; Thouret, 2002). The development context of Peru, with few means to cope with disasters, was highlighted and thus became one of the major issues of this paradigm.

In the wake of the work of Peruvian scientists and practitioners, the first operational project called "Eaux de source au Pérou" (EDSAP: "spring water in Peru," Levieux et al., 2007) coordinated by Anthony Finizola (LMV), through the French based NGO "Volcan-Explor-Action" (VEA). The purpose of this project was to establish a first awareness center at the Museo Andino with the implementation of educational posters, still hung as of 2020.

A group of researchers from the USGS, UNSA, the University of Buffalo (Unites States), the National Autonomous University of Mexico (UNAM) and the LMV constructed an essential volcanology tool: the hazard map of El Misti volcano. The construction of the hazard map was intended to consider several types of hazards: 1) hazards related to pyroclastic flows on the slopes of the volcano, 2) hazards generated by ballistics and tephra, 3) hazards related to lahars, and finally 4) hazards related to possible rock avalanches caused by the collapse of a flank of the volcano. This hazard map was finalized and published in 2006 (Mariño et al., 2006). We will show that it became an important interface around which the stakeholders in charge of volcanic monitoring and then those of risk management in Arequipa gathered in the framework of their activities. In particular, it was mobilized for the organization of the first public event related to risk management: the first simulation of a volcanic eruption of El Misti in 2009 with the participation of all the stakeholders in charge of risk management (INDECI, COER, and DRMPMA) and the volcanic observatories of INGEMMET and IGP.

Since 2005, INGEMMET has organized seven international forums on volcanic risk (2005, 2006, 2007, 2008, 2010, 2013, and 2015) with an increasing number of presentations from foreign participants, both from southern and northern countries. They also started the monitoring of Ubinas volcano in 2006. The eruption of Ubinas volcano between 2006 and 2009 (in the region of Moquegua, bordering the Arequipa region) was a catalyst in the organization of the first volcanic eruption simulation in Arequipa (2009). Indeed, for the first time, stakeholders had to manage an eruptive crisis that threatened villages, and they managed to successfully evacuate inhabitants (Rivera et al., 2010), despite facing very complicated conditions (lack of staff, knowledge and organization of the authorities).

In 2011, the Risks Awareness Center[1] opened in Arequipa to raise awareness of the various seismic, electrical and volcanic risks. The creation of the center is a decision of General Carlos Nacarino of the INDECI following the magnitude 8.4 earthquake that hit the city of Arequipa in 2001, and that left a deep trace in the memory of the inhabitants. It was intended for schoolchildren of the Province and reflects the dialogue that has been operated between a number of actors, as the development of the different educational rooms of the center was made through the participation of all actors in charge of monitoring and management of volcanic risks (INGEMMET, IGP, INDECI, COER, DRMPMA, and VEA).

After being hosted in the premises of the INDECI, with few resources to carry out its activities, INGEMMET inaugurated in 2013 its first volcanic observatory place in Arequipa and continued to work with LMV scientists on a second operational project with Peruvian school children called "Geoscientific communication problem with communities for disaster prevention and land planning in Peru" (Macedo et al., 2014).

In 2013, all the actors of risk management in Arequipa, COER, INDECI, DRMPMA, as well as the institutions in charge of volcanic monitoring (IGP, INGEMMET, UNSA) created a coordination platform for volcanic risk management, but its sustainability was difficult to maintain and raised many discussions. In 2014, Peru adopted its first plan for a national disaster risk management system (SINAGERD, 2014) that was implemented at different scales (national, regional, and local). This new structuration will permanently change the consideration of volcanic risk management in Peru, especially for Arequipa, by allowing a link between national risk management policies and their local application, with financial means and stronger inter-institutional coordination.

The "Café con ciencia" has been organized in 2019 by the IRD, the LMV and the Alliance Française in Arequipa (with the presence of INDECI, INGEMMET, and DRMPMA). Other recent projects—many of which are still ongoing -, are being conducted in the Arequipa region, such as the one on risk reduction in the town of Caylloma around the Sabancaya volcano by the NGO PREDES (Center for Disaster Studies and Prevention) between 2018 and 2020. This NGO, involved for 10 years in risk reduction in the region of Arequipa, joined a new actor, the NGO ADRA (Adventist Development and Relief Agency) to inaugurate in 2020 a new project called, "Preparados Ante Volcanes y Sismos" ("Prepared to face Volcanoes and Earthquakes") that consists of developing early warning systems in the regions of Arequipa (El Misti) and Moquegua (Ubinas), as recommended by the UNDRR. In addition, an interactive 3D map of the risks related to El Misti has been built between 2014 and 2020 by INGEMMET.

Further studies were developed on volcanic risk perception in Arequipa, such as the project "Risk perception around el Misti Volcano" in two neighborhoods of Arequipa variably exposed to hazard risk (Jacquez and Rouquette, 2021, in collaboration with the Geophysical Institute of Peru (IGP)). Another project is being conducted by the IGP around volcanic risk perception coordinated by Luisa Macedo (Andina, 2021) with a population of about 5,000 university students in Arequipa. In the meantime, IGP opened in 2018 his new volcanic observatory in Arequipa named CENVUL (El Centro Vulcanológico Nacional), and inaugurated his new building in 2022.

New activities based on geological heritage emerged in Arequipa in the 2010s (led by INGEMMET). They aim to consider such heritage and the role of the Earth sciences and governments in the preservation of geological sites of interest (Gray, 2004; Brocx and Semeniuk, 2007) and in particular the construction of a new UNESCO program around geoparks (Patzak and Eder, 1998). Between 2013 and 2019, Benjamin van Wyk de Vries engaged in theoretical deepening and reported on the need for geoheritage to develop knowledge and find new ways to answer questions posed by society, pointing to the difficulties of dialogue between different stakeholders facing disaster risk who have a different use of science (van Wyk de Vries, 2013; Olive-Garcia and van Wyk de Vries, 2017). In 2019, he argued that it is necessary to establish a relationship between hazard and risk *via* the design of geosites (van Wyk de Vries and Vereb, 2019).

In 2018, van Wyk de Vries and a group of international colleagues proposed the UNESCO International Geoscience Programme project n°692 'Geoheritage for Geohazard Resilience, in which the inventory of potential geosites around Arequipa was made (Salazar et al., 2021). The geosites are characterized by a set of geological and landscape areas, with different levels of protection and vulnerability, in which all the information on the local human presence, geosphere, and biosphere are made available to increase awareness of the overall risk.

The "Ruta de Sillar" (the Sillar route) is a tourist excursion that takes visitors from the historic city, to observe the Inca terraces above Arequipa and El Misti volcano, and then visits the Sillar quarries at Añashuayco, the extraction area of the Sillar stone. The Sillar quarries and the canyon are high risk areas, frequently affected by floods and debris flows. The conception of

1 Translation from spanish: "Centro de sensibilización de riesgo de desastres".

the Sillar Quarry as a geosite has led to a discussion with the miners in place (for whom the extraction of Sillar is a basic income), as well as other actors (INGEMMET, IRD, and UNESCO) in order to further develop this geotouristic zone to raise awareness of natural risks, while increasing the tourist offer, increasing visitation, integrating safety measures, and importantly assisting in the regularization of the quarrymen's legal posession of their lands and workplace.

The consideration of the communities with respect to volcanic environments and risks prompted numerous presentations at the "Volcanes y Comunidad" colloquium by INGEMMET in August 2020, mainly around the Latin American geology community, and also in other international meetings. Another geosite project, "Ruta de Huayruro" in Omate (Moquegua, 70 km from Arequipa), was also initiated by INGEMMET to raise awareness of the Huaynaputina eruption in 1,600 (VEI 6) that devastated several villages (Mariño et al., 2021). The first geotourism excursion was organized on the Ruta de Huayruro in April 2020.

This history allows us to account for the emergence of subsequent practices that Peruvian practitioners and local actors have developed in its wake. For example, the hazard map has become a fundamental mediation tool around which risk management is organized for the institutions of COER, CENEPRED, INDECI, DRMPMA. New simulations of volcanic eruptions of El Misti were carried out in 2010, 2018, and 2019, contributing to the knowledge of the hazards posed by the volcano. Since 2018, the regional government of Arequipa has issued an executive resolution enthroning the month of April as "Volcanology Month" in the region of Arequipa, during which many events are co-organized by INGEMMET and the regional government of Arequipa for professional and civic audience. The technological development that Peru has experienced in the last 30 years with the massive use of social networks, also allows institutions to communicate and Arequipeños to be better informed about the eruptive potential of the volcano, which is also considered with pride and an emblem for the city.

Results

This history has allowed us to identify and select a significant amount of practices around the development of volcano monitoring and disaster risk management in Arequipa. We propose to use this history as a basis to account for the affiliation of these different activities with the paradigms of vulnerability and resilience.

First, as stated by Foucault (2001), Foucault (2009), the apparatus is an arrangement of plans, stakeholders and institutions, theoretical frameworks, events, projects, tools, places, i.e., elements that we can point to in our narrative as risk management practices that have been fundamental to the development of risk management in Arequipa.

- There are several theoretical frameworks: they are the result of a thorough theoretical structuring of an idea (volcanic hazards as a whole, or studies on the eruptive processes of volcanoes) and are therefore important elements to develop a common knowledge around risk management, validated by peers. We documented many studies that have been conducted in Arequipa and have led to a great improvement of the initial situation on volcanic risk management (Macedo, 1994; Juvigné et al., 1997; Thouret et al., 2005; Thouret et al., 1995; D'Ercole et al., 1994; Thouret and D'Ercole, 1996; Thouret, 2002; Masuno Kosaka et al., 2000; Degg and Chester, 2005; Rivera et al., 2010; van Wyk de Vries and Vereb, 2019).
- There are also projects carried out by similar actors or in connection with theoretical frameworks, as operative projects that have an influence on risk management actors but also on local populations ("spring water in Peru," Levieux et al., 2007; Macedo et al., 2014; Jacquez and Rouquette, 2021, Andina, 2021), in collaboration with the Geophysical Institute of Peru (IGP) and the UNESCO International Geoscience Programme project n°692 'Geoheritage for Geohazard Resilience in collaboration with Geological institute of Peru (INGEMMET) (Salazar et al., 2021).
- There are tools that are generally developed in the framework of risk management, mostly in the vulnerability one (the Hazard map; the Risks Awareness Center, a coordination platform for volcanic risk management, early warning systems, interactive 3D map of the risks, Geosites).
- In this apparatus we also find events that allow to create links between risk management professionals and the population to raise awareness about volcanic risk management (the first simulation of a volcanic eruption of El Misti in 2009, INGEMMET's international forums (2005–2015), "Café con ciencia," "Volcanes y Comunidad" colloquium, The first geotourism excursion, "Volcanology Month" in April).
- Finally, the apparatus is composed of a myriad of institutions: INGEMMET (established in 2013); CENVUL-IGP (established in 2018); INDECI; CENEPRED; COER; DRMPMA; ADRA; PREDES that have learned to collaborate together over 30 years.

All these risk management practices have contributed to forming this apparatus, but we can further analyze what allowed their emergence and structuring in Arequipa.

Second, we can retrospectively identify two major sets of studies that provided a significant anchor and agenda for subsequent practices in Arequipa: first, the reflections by Robert D'Ercole and Jean-Claude Thouret based on the vulnerability paradigm (D'Ercole et al., 1994; Thouret and D'Ercole, 1996; Thouret, 2002), and then those of Benjamin

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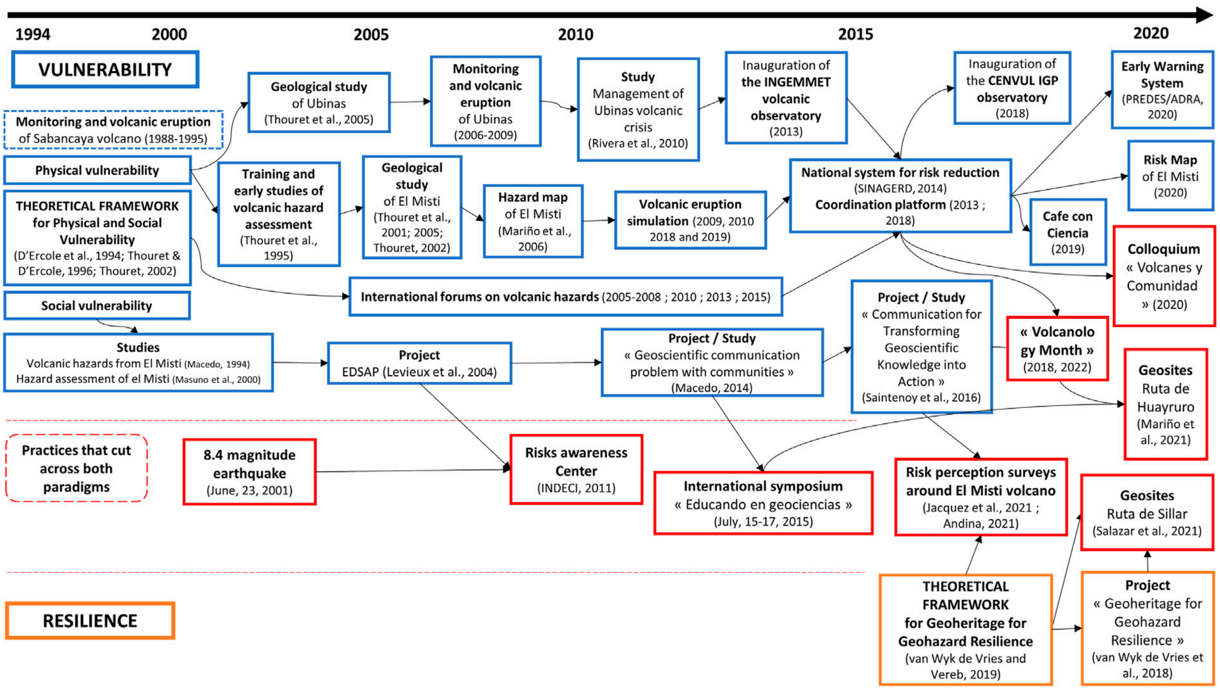

FIGURE 3
Genealogical map of the practices between vulnerability and resilience in Arequipa (1994—2020).

TABLE 2 Theoretical framework for Physical and Social Vulnerability' in Arequipa.

"According to the etymology, vulnerability is the fact of being vulnerable to injury, attack or having trouble in recovering endangered health. This definition implies two effects of vulnerability to natural hazards: on the one hand, the potential damage or the capacity to damage threatening natural phenomena and, on the other hand, the difficulties that an ill-prepared society encounters in reacting to the crisis and then restoring the balance in the event of a disaster (direct and indirect, immediate and lasting disruptions). These two aspects refer to two approaches to the system of vulnerability: the classic one is to measure the potential damage of the elements exposed to the threat; the new one, integrated and complementary to the first, aims to identify the conditions or factors conducive to damage or influencing the capacity to respond to a crisis situation. The aim of this new approach is to be used for operational research and the development of preventive planning in urban areas, particularly in developing countries (Dcs)." (Thouret and D'Ercole, 1996:407).
"Towards a new paradigm? In the face of natural disasters that are causing more and more damage in developed countries (about 100 billion dollars in Kobe, Japan, in 1995), we must change the way we think about risk management. This change is based on the fact that our societies are becoming more vulnerable to natural hazards because they result from the complex interaction between natural phenomena, socio-economic systems and behavioral patterns, which can only be partially predicted. In order for a society to be able to tolerate damage without external assistance and to overcome the loss of productivity and reduction in quality of life caused by a disaster, Mileti (1999) set several objectives that can be grouped under the paradigm of sustainable development. Once risk is defined through interdisciplinary work, the first step is to disseminate scientific knowledge of hazards in a language that the public can understand, to provide multidisciplinary education, and to train personnel responsible for damage mitigation and risk management. A national hazard and risk assessment should be conducted to examine the interactions between the country's natural and social systems and infrastructure that influence the effects of damaging natural events. Another objective is to record mitigation efforts and the cost of recorded losses in an internationally accessible database. As community resilience to natural hazards is essential, it must be enhanced by improving the quality of life and environment of the population and ensuring equity between and within racial, social, and generational categories. Thus, local actors must identify potential risks and then adopt a consensus regarding acceptable risk, as it is at the local level that this responsibility must be promoted. At the national level, scientific knowledge about hazards must be applied appropriately to reorient development projects, and a legislative and institutional framework must be redesigned so that regulations and programs concerning risks and sustainable development are integrated into a coherent governmental project. Finally, the retrospective review of past experiences is essential to measure the progress made in the field of risk management for sustainable development.'. (Thouret, 2002:521–522).

van Wyk de Vries based on the resilience paradigm (van Wyk de Vries and Vereb, 2019). In order to better understand the influence of these scientific studies, we propose to represent the set of practices carried out in Arequipa through a map in a genealogical perspective (see Figure 3). This representation highlights the importance of these seminal studies that we

TABLE 3 Theoretical framework for Geoheritage for Geohazard Resilience in Arequipa.

"Natural hazards come from geosphere processes combined with the atmosphere and hydrosphere. Resilience is the ability of a population to resist and adapt to these natural hazards and even profit from them. Geoheritage is the appreciation and characterisation of geological features in relation to humanity. Geoheritage can be used to communicate natural hazards and relate them to risk, and could be especially valuable for developing countries, where resources are limited. This is done through geosites, the basic building block of geoheritage. A geosite is a location or area (e.g., outcrop or landscape feature). An area can be divided into different geosites, as basic units of the geology and landscape. This division provides a way of characterising the whole equation of risk (e.g., hazards + vulnerability = risk), as in each geosite information on all aspects of human presence (and biosphere) can be integrated. The geosite in this way becomes the unit area to characterise the whole risk problem, and can be used to work on all aspects of resilience in one coherent way. We provide examples of our first attempts of holistic geosite mapping that will be used for a global project called Geoheritage for Resilience. This is a network to develop geosites around the world in areas of natural risk that can be developed to describe geosites of special interest, protect them and use them to develop integrated risk assessment, mitigation and communication strategies. We provide examples from project sites such as the Macolod Corridor (Philippines), Dallol (Ethiopia), Ometepe Island (Nicaragua). Each site will be developed according to the local possibilities and resources. However, with a global network run *via* scientific social media, each site can help the other and pool resources, to maximise the development of geosites for resilience worldwide. Benjamin van Wyk de Vries and Viktor Vereb (2019).
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consider retrospectively as a theoretical framework that guided the practices carried out over 3 decades in Arequipa.

Indeed, it is through the studies of Jean-Claude Thouret (considered as a "Theoretical framework for Physical and Social Vulnerability" in Arequipa[2], see Table 2), that can be seen to be the starting point of the whole volcanic risk management apparatus in Arequipa (including both the physical and social component of vulnerability). This apparatus shows a great variety of elements: geological studies of El Misti, projects like new early warning systems, tools like the map of hazards and risks, places like the volcanic observatory of the INGEMMET and events like the simulations of volcanic eruption or the "Cafe con Ciencia." It should be noted that a natural event like the eruption of the Ubinas volcano plays a role in the apparatus. Among the actors who participate in this apparatus, we can distinguish official institutions in charge of volcano monitoring, volcanology research laboratories, organizations in charge of the risk management plan but also mayors, the Andean museum, the Alliance Française, and also NGOs. All of these elements gradually transform a theoretical framework into an operational apparatus. We can note in this regard that this operational apparatus was co-constructed between risk management practitioners, volcanological engineers and scientists in a spontaneous way while there was only a weak institutional structuring around risk management in Arequipa and few means to develop it. Indeed, it is only since 2014 with the establishment of SINAGERD that Peru has had a risk management policy articulated between the local and national levels. Thus, local risk management practices have significantly increased interest, funding, and knowledge dissemination in the city of Arequipa, as well as the institutional structuring of risk management with a specific program.

The resilience-centered volcanic risk management apparatus in Arequipa developed in the Geoheritage for Geohazard Resilience project also starts with a "Theoretical framework for Geoheritage for Geohazard Resilience" in Arequipa (see Table 3).

Van Wyk de Vries investigates approaches based on the social vulnerability paradigm but introduce resilience operations through geosites design. Indeed, the geosites are not only tools with a defensive vocation: they emerge thanks to the co-construction with stakeholders initially not concerned by risk management but affected by risk (the miners of the Sillar quarry), they have the vocation to respond to the tourist demand while respecting the geological heritage, and above all, they are educational and sensitive apparatuses that include artistic approaches (realization of frescoes by the miners) as much as sensorial landscape places.

Practices are less numerous for the "Theoretical framework fo Geoheritage for Resilience" because of the recent history of the apparatus, which started just in the last few years. On the other hand, this apparatus will play a specific role depending on the places chosen for the geosites. The same stakeholders are involved in this apparatus as in the vulnerability apparatus, which proves the interest of this approach but also its complementarity in relation to the vulnerability one, in which they are all involved. In Arequipa, there is an articulation between the two paradigms that can be described as a paradigm of physical and social vulnerability, with social vulnerability being mitigated by resilience operations such as the geosites and the risks awareness center, because the choice of locations is partly based on the well used equation: Risk = Hazard + Vulnerability.

2 Text in Tables 2, 3 were translated from french.

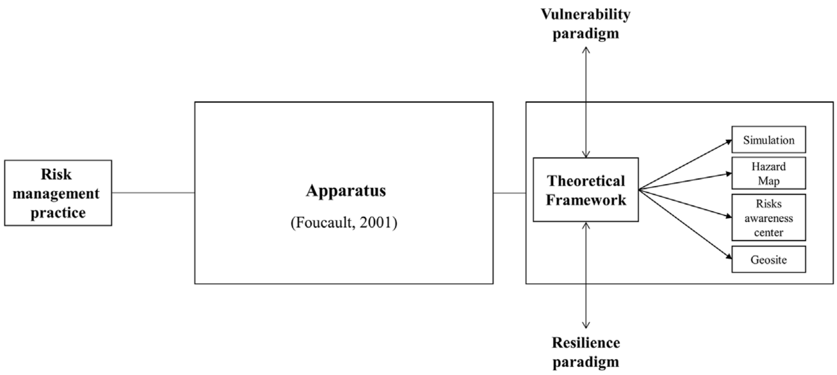

FIGURE 4
Framework for risk management practice between vulnerability and resilience.

We question the articulation between the vulnerability and resilience paradigms in Arequipa through practices which are not all linked to a single Theoretical framework but both of them. Indeed, risk perception is the end point of the "Theoretical framework for Physical and Social Vulnerability" (Thouret, 2002): "As community resilience to natural hazards is essential, it must be enhanced by improving the quality of life and environment of the population and ensuring equity between and within racial, social, and generational categories." Thus, local actors must identify potential risks and then adopt a consensus regarding acceptable risk, as it is at the local level that this responsibility must be promoted. Risk perception is also the starting point of the "Theoretical framework for Geoheritage for Geohazard Resilience," which implies the presence of four border objects, straddling the two paradigms that establish connections between them. These are:

- The project of the Ruta de Huayruro carried by the stakeholders of the "Theoretical framework for Physical and Social Vulnerability," and influenced by the contributions of the Geoheritage section at INGEMMET. We justify their place here in the transition they make towards the consideration of factors related to awareness and education: "these resources can help promote awareness of geological risks through dissemination and education, which aims at mitigating the risk of disasters" (Mariño et al., 2021);
- A link can also be made between the studies conducted on geoscientific communication around the "Theoretical framework for Physical and Social Vulnerability" that lead to the design of Ruta de Huayruro (Macedo et al., 2014; Saintenoy et al., 2016) and the current projects on risk perception around El Misti that approach the designs of the "Theoretical framework for Geoheritage for Geohazard Resilience" (Jacquez et al., 2019; Andina, 2021);
- The Risks Awareness Center, whose initiative emerges due to an expert in the field and whose objective is to enable the dissemination of knowledge on risks. This approach was initiated and made possible due to the personal initiative of General Carlos Nacarino, who succeeded in surrounding his idea with entrepreneurs from the region to finance it. This center is at first a pedagogical tool that fits into the paradigm of social vulnerability, but the individual initiative of the general coupled with the participation of citizens and institutions involved in risk management, has allowed a bottom-up co-construction that we consider as a resilient approach. However, local communities that experience the risks were not involved (except for financial support), but only invited to come and experience it once it was constructed. This is why we will place it at the junction between the two paradigms;
- The "Volcanes y Comunidad" colloquium, brought together stakeholders from both theoretical frameworks around presentations oriented to vulnerability and risk perception in a resilient approach.

We propose a complete representation of both risk management apparatuses that have been built up over 30 years around the two main theoretical frameworks related to an apparatus, with the representation of these border objects that reflect the porous boundaries between the two paradigms (see Figure 3). The question of genealogy is always in the background with Michel Foucault's work, as he pays particular attention to the history of apparatuses, and to the way in which the links are constituted throughout history (Foucault, 2009). That is why we suggested a genealogical representation that documents the emergence of different practices over 30 years, and highlight their place in the vulnerability and resilience paradigms.

Regarding the articulation between the two paradigms of volcanic risk management in Arequipa, the vulnerability paradigm structures the whole, it appears in both the physical and social aspects. The proposition around the Theoretical framework for Geoheritage for Geohazard Resilience can be described as a place-based resilience operation from a classical vulnerability approach, as another way of understanding social vulnerability.

We could also integrate other elements of the apparatus, such as the doctrines of institutions, and the logics of power between actors in further work as proposed by Donovan (2017). We are aware that such a conceptualization implies rather top-down structural logics of knowledge transfer between North and South (Bankoff, 2004; Gaillard et al., 2010). However, the theoretical framework could be the creation of local stakeholders that will organize themselves around a singular idea to defend, which could be the first link towards the realization of community activities based on its own decisions to build a common meaning. With our proposal, we show that we can design a risk management apparatus thought to include participatory approaches with citizens of the civil society (Cadag et al., 2018). Indeed, a study suggests energising this stream around livelihoods through the practice approach (Sakdapolrak, 2014). We point out that the field of livelihoods is absent from studies on El Misti volcano, while it is considered a fundamental factor in both paradigms, in other volcanic areas, including nearby ones such as Ecuador (Kelman and Mather, 2008; Barclay et al., 2019).

Finally, the last point to be addressed is the role played by studies on the differentiated perception of risk by the inhabitants in the management of volcanic risks. It is interesting to note that several surveys are undertaken in both the vulnerability and resilience apparatuses. But what to do with the results of this type of investigation? In the vulnerability paradigm, it can be used as an indicator of the difficulty of building a consensus around the perception of risk. In the resilience paradigm, it can be used as the first step in a new approach to risk management, which would consist of mapping the worlds of sensitivity in volcanic risk management and using this mapping to co-construct an apparatus (Lièvre et al., 2021). The challenge is to build an apparatus along the way that avoids the collapse of meaning for this wide variety of actors. The construction of meaning (sensemaking) is the prerequisite for actors to behave in an extreme event, a volcanic eruption (Lièvre et al., 2019). In this perspective, the set of operations linked to the vulnerability paradigm could be considered as a part of the anticipatory capacity of a resilience approach (Hollnagel et al., 2006).

Conclusion

We participate in the extremely rich, fertile, but complex debates between vulnerability and resilience within geography and Earth sciences by proposing to approach them from the paradigm perspective in Kuhn's sense. As we have shown, this is a plausible interpretation we can make of these debates (Dauphiné and Provitolo, 2007; Cutter, 2018). We are moving historically from the vulnerability paradigm to the resilience paradigm in risk management. The transition from one paradigm to another is always a radical change of viewpoint that can better integrate a number of questions posed by the previous paradigm. Thus, we have suggested distinguishing the two paradigms in a radical way by pairs of contrasts, in order to better situate the oppositions but also the links that can be established between these two ways of understanding risk management.

We have shown the relevance of mobilizing this paradigm grid of vulnerability and resilience to account for the evolution of volcanic risk management practices in Arequipa from the 1990s to the present. The vulnerability paradigm implies developing defensive activities around the eruptive potential of El Misti. For example, new early warning systems, a national risk management system, studies of the probability of being affected by the risks based on calculations... Shortly, practices that aim to calculate, control and minimize the risk. Despite the work carried out in Arequipa, this approach teaches us that it is difficult for the population to imagine the risks caused by a potential eruption, having never had the experience of this type of event. There is an awareness at the local level that disaster prevention also depends on the resilience of society, that is, the local capacity to cope with disasters of volcanic origin. A factor that tends to be minimized in the technology-based vulnerability paradigm. This implies thinking about other, more offensive strategies that we consider under the umbrella of the resilience paradigm.

From 2015, a secondary theoretical framework appears around geoheritage and resilience. We suggest to refer to Table 1 to understand the place of this theoretical framework between vulnerability and resilience. First, it is centered on risk rather than on uncertainty, as something we do not know in advance, but it tends towards the resilience paradigm by taking the territory and the capacity to adapt as a basic principle. Secondly, it emphasizes the involvement of the human factor, which is the starting point of the solution to a problem in the resilience paradigm. Geosites are a more grounded approach around risk knowledge, as they are "units" that holistically bring together what was previously generally separated. The geosite is a site where risk can be experienced, it is not only cognitively apprehended out of context but corporeally. It thus implies this pedagogical dimension in situation, bringing a pedagogical value to the apparatus. Finally, the geosite is also an essential place to live for certain workers (the miners). The geosite brings an essential "ecological and corporal anchoring" on the risks that are contextualized instead of being only "perceived" by surveys on risk perception whose results do not seem to show a particular evolution in Arequipa.

Nevertheless, the starting point of geosites in this case is places deliberately identified as particularly vulnerable (natural and societal). Therefore, we consider the geosite as a resilient operation but with a theoretical framework at the junction between the vulnerability and resilience paradigms. Practically, this geoheritage work has had the effect of assisting the local people in stabilizing their livelihoods and social situation, and with improved economy and standing assisted them to defend their interests, and take a lead in their own disaster risk reduction practices from their own point of view backed up by the scientific community. There are links between practices around vulnerability and resilience but some of them are independent, separate and autonomous as the risks awareness center, a spontaneous resilience operation that does not refer to a theoretical framework. It is a highly practical personal response.

We narrated 30 years of the history of volcanic risk management in Arequipa and used the notion of "apparatus" as a methodological tool in the sense of Foucault (2001); Foucault (2009) to highlight and order the different practices. As we mentioned, by entering the apparatus understood as a set of heterogeneous elements linked together in order to produce an activity, we find links with assemblage theories (Donovan, 2017; McGowran and Donovan, 2021) based on Latour's work (2006). We analyze this apparatus, not directly through the actors, but through the manifestation of what they do: they produce theoretical frameworks; make studies, maps, simulations; organize symposiums and workshops; set up projects and build up institutions. It includes many elements, of different forms: theoretical frameworks, geological studies, hazard map, risk map, simulation, symposiums, forums, surveys on risk perception, café con ciencia and geotourism.

The apparatus makes it possible to identify both the local anchoring of these activities (geosites, simulations, etc.) and the ideal or theoretical elements that are sometimes external to the local context and yet play a decisive role in the development of the apparatus. We produced a genealogical map (Figure 3) of the apparatus that provides a historical account of the evolution of risk management practices in Arequipa. We then highlighted the specificity of the theoretical framework that allows to order and energize all the elements of the apparatus, in an assemblage, relative to the context of Arequipa in Southern Peru. We found that the "paradigm" in the sense of Kuhn (1972) could be associated with vulnerability and resilience to document volcanic risk management. The apparatus is the arrangement that makes it possible to account for the effective links between the theoretical framework, itself anchored in a paradigm, and the development of activities by risk management actors (see Figure 4 below). We must precise that the links highlighted pre-exist the researcher's analysis and constitute the "performance" of the collective action (Gilbert and Raulet-Croset, 2021) thanks to the activities carried out over a long period of time.

This proximity shows that we can better link together the scattered activities carried out by the actors that are sometimes difficult to organize around a common thread. The apparatus organizes all the activities and allows to bring out in a concrete and orderly way what has already been realized under the aegis of a theoretical framework, in a non-linear way and not always conscious by the actors. Furthermore, it is possible to mobilize this theoretical framework in a general way beyond the single case of Arequipa, to document volcanic risk management practices elsewhere in the world between vulnerability and resilience as recommended by recent studies (Miller et al., 2010; Fekete et al., 2014).

We showed the strength of the theoretical framework and the academic works to enroll people and develop activities around an idea. Nevertheless, these studies are mostly conducted by foreign Western scientists, which is a limit from the point of view of the self-determination of local actors in the production of ideas. The major problem is structural, Peru does not have university structures as important as in the West in the field of volcanology, which implies an important transfer of knowledge from North to South (Gaillard et al., 2010). However, scientists have also promoted the learning of Peruvian actors by allowing them to study in France in master's degree programs, which has considerably increased local know-how, skills and development of observatories in volcanology. Thus, along the way, the initiative initially carried by the "North" slides towards the assumption of responsibility by the "South" for its own practices and ideas to develop. The independent civil defense center (risks awareness center) was an early form of this, and the geoheritage program, based on prior community consultation and working with communities. In this latter, the external actors (international researchers) take a secondary role in an activity fully integrated with the locals. The "international experts" are integrated into this apparatus as members, financiers, advisors but are no longer "top dogs," but rather one of the pack.

The political and institutional implications of these analyses suggest that we need to invent new ways of organizing ourselves in the face of a potential volcanic eruption, in addition to those developed in the vulnerability paradigm. In this case, it would be necessary to develop proactive strategies located as close as possible to the population. Each district of Arequipa has a district mayor around whom "juntas" (councils) are organized to deal with issues involving the members of these communities. These are opportunities to develop livelihoods (Kelman and Mather, 2008; Barclay et al., 2019) at the intersection of scholarship and practices that include knowledge, politics, scales and different dynamics at the scale of a territory (Scoones, 2009). There are therefore opportunities for finer articulation between the different scales of a territory, and this by encouraging new practices closer to the actors, those who live the risks, and not only in a representational dimension of risk.

We can identify limitations of this research as areas for research development. The different elements highlighted thanks to the apparatus as a methodological tool should be better qualified generically, the links that have been established between them should be better identified and the coherence of the whole should be discussed. It would be also necessary to carry out an exhaustive study of the existence of genealogical maps documenting volcanic risk management practices. We suggest extending the notion apparatus in future research in greater depth in relation to the management literature (McKinlay and Starkey, 1998; Gilbert and Raulet-Croset, 2021) as a powerful way to document the way people organize themselves. In addition, this theoretical framework fits with the perspective adopted in the Disaster Risk Management Assemblage (DRMA) (Donovan and Oppenheimer, 2014; Donovan, 2017, 2019, 2021; McGowran and Donovan, 2021). The work of Gaillard offers insights to improve risk management (Gaillard, 2010; Gaillard et al., 2010; Gaillard and Mercer, 2013; Gaillard, 2022).

We could also link this work with the theoretical framework of epistemic communities (Amin and Cohendet, 2004). Indeed, we can understand the path of each apparatus initiated by a researcher who has enlisted a certain number of partners to transform the theoretical framework into an operational apparatus - a code-book - by mobilizing the theory of epistemic communities. The literature on the notion of epistemic community in the field of political, economic and management sciences (Haas, 1992; Cowan et al., 2000; Amin and Cohendet, 2004) proposes to document the conditions that will allow a theoretical manifesto to be incorporated into the field of practice. An epistemic community is a learning community where meaning is negotiated between heterogeneous actors. Cohendet et al. (2017) propose a grid, in his middleground theory, where the elements of a management apparatus on a territory must articulate fundamentally: manifesto, project, place and event. The broad categories proposed by Cohendet are found in both apparatuses, which establish the existence of a potential learning community. The interactions between the actors in relation to their variety in each apparatus should be better documented. It can be pointed out that maps and plans play an important role in the vulnerability apparatus and similarly that places play a particular role in the resilience apparatus. One could say that there is an event deficit in the resilience apparatus: a scheduled event that would have some recurrence.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

Consent was obtained from the individual(s) for the publication of any potentially identifable images or data included in this article.

Author contributions

PL made the major contribution in this article by proposing the idea and writing the theoretical demonstration on paradigm, vulnerability, resilience and apparatus. EM conducted a literature review to accompany the theoretical demonstration. She also conducted the field survey, wrote the resulting narrative, and produced the concept map. JM and BWV brought their expertise in the fields of geography and Earth sciences to help us initiate this interdisciplinary discussion. Their theoretical contributions and reviews have been decisive in improving this work. LM, DR, MR, and PM provided important factual elements to write a narrative that is as close as possible to the practices carried out over the last 30 years in Arequipa. They also reviewed the proposed narrative.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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