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A cross-category analysis of high impact low occurrence (HILO) disasters

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ABSTRACT

This paper explores six High Impact Low Occurrence (HILO) disasters, generating insights from five different categories associated with them, namely causes (geophysical, technological, biological, sociological), phases (preparedness, response, recovery), dimensions (socio-economics, governance, equity), sectors (health, education, infrastructure, economy) and national contexts with differing levels of economic development. The process involved the generation of a questionnaire, based on a literature review; and the subsequent analysis and discussion of the questionnaire responses made by six experts nominated by six academies of science in Asia. The findings highlight the limitations of probabilistic, frequency-based risk models for HILO disasters and instead emphasise the importance of scenario-based (worst-case) analyses; mechanisms that preserve inter-generational knowledge, institutional continuity and community-based early-response networks; strengthening community resilience while ensuring equity; and making appropriate investments for increasing preparedness, if not through structural interventions, at least through sustained awareness programs and periodic drills. Theoretical contributions include arguments that institutional capacity, governance quality, and social resilience are more decisive determinants of HILO event outcomes than probabilistic risk analyses; and that effective preparedness depends more on anticipatory planning, scenario-based training and institutionalised memory rather than experiential learning; thus advancing HILO theory beyond event-centred and frequency-driven interpretations towards a more governance- and resilience-oriented understanding.

1. Introduction

In recent decades, the global risk landscape has changed significantly with new and emerging risks. Infectious diseases, climate change, environmental degradation, cyber-attacks, and terrorism can be seen not only as risks *per se*, but also as magnifiers of other risks [1], forcing communities globally to anticipate and prepare for unpredictable disasters [2]. At the same time, high-impact, low-occurrence (HILO) disasters pose even greater challenges due to their potential to cause catastrophic consequences, especially given the reluctance of governments worldwide to invest against them because of their low frequency of occurrence.

HILO disasters are events that, while rare, have the potential for significant damage and disruption when they do occur [3]. They

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are often unpredictable, difficult to imagine and can overwhelm communities or systems that are not adequately prepared [4]. HILO disasters often surpass the coping capacity of the communities affected. Hence it is often stated that such events need to be given more prominence than what the statistics imply [5]. They include disasters such as large earthquakes, tsunamis, nuclear power plant meltdowns, volcanic eruptions and pandemics. These disasters require extensive preparation and mitigation efforts due to their severity, even though they may not occur frequently.

HILO disasters can be broadly divided into those triggered by geophysical hazards (such as tsunami, earthquakes), biological origins (pandemics), technical and industrial events (nuclear powerplant accidents), socio-political phenomena (major conflicts, economic crises), environmental crises (collapse of major ecosystems) and human actions (terrorists attacks). Each of these causal scenarios involve events with the potential for severe consequences, even though their likelihood of occurrence could be relatively low.

It is not only by causes, as described above, that disasters can be categorized. Other relevant categories associated with a disaster are its phases (e.g. response and recovery) and context (e.g. country of occurrence); also, the sectors affected by it (e.g. health and education) and dimensions along which it can be analysed, such as socio-economics, governance and equity. It is indeed such a cross-category analysis that we intend to pursue, given the relative paucity of such analyses in the literature.

Despite their low occurrence, statistics indicate that the extensive losses and damage caused by HILO disasters are much greater than those caused by recurrent ones [6]. Especially when considering human lives lost, HILO disasters tend to be catastrophic when compared with others. For example, the DesInventar database [7] for Sri Lanka indicates that the single Indian Ocean Tsunami of 2004 accounted for around 33,000 dead or missing, which is 83% of all deaths from all disasters (other than COVID-19) since 1974. However, the people affected in various ways (e.g. through injury, damage to dwellings, displacements etc.) due to this single event only amounts to around 1 million, or 2% out of the 45 million affected through other disasters, mainly the almost annual droughts, floods and high winds - this number includes multiple times individuals have been affected, if any. The former statistic highlights the high impact of the single (HILO) tsunami event, while the latter the fact that other disasters are far more frequent – hence demanding attention in the form of investments for preparedness and mitigation measures, attention that is diverted away from becoming ready for a possible future tsunami.

There are, admittedly, some recurrent disasters that have high impacts too, such as the annual flooding in Rio Grande do Sul [8]. Emerging climate extremes are modifying historical hazard baselines, making previously rare or low-probability events more likely or more severe [9]. Rising temperatures, altered rainfall patterns, and increasing frequency of extreme weather are producing conditions that exceed past records, thereby challenging assumptions derived from historical averages. As a result, disaster management systems, infrastructure design standards, and preparedness protocols that are often calibrated against past recurrence intervals are being exceeded, revealing institutional and planning weaknesses. Consequently, climate change is shifting HILO events from unlikely to increasingly plausible scenarios, underscoring the urgency for more anticipatory and adaptive preparedness strategies.

However, another defining characteristic of HILO disasters is that they are also unpredictable and fall outside the normal expectations based on historical data. Without frequent occurrences or reliable historical patterns, forecasting such disasters becomes nearly impossible [3]. Risk assessments often rely on historical patterns, but for HILO events, the lack of frequent data points results in an incomplete understanding of potential risks and impacts [10]. Therefore, it is difficult to anticipate and plan for them. Even if a potential risk is known (like earthquakes or pandemics), predicting the exact magnitude or range of impacts can be highly uncertain. Further, the cascading impacts that could be triggered from HILO events are also difficult to predict and prepare for [11]; for example, as described in what follows later, although Japan is generally well prepared against earthquakes and tsunamis (which are not low probability hazards for that country), the triggering of a nuclear reactor disaster due them was not easy to anticipate. This unpredictability makes it hard to assess the full extent of the preparedness measures required. Such uncertainty, especially regarding cascading effects, are also due to the increasing complexity of our modern world – for example, a localized volcanic eruption can have implications for air transport and global supply chains [12]. Although scenario-based futures studies could remedy the above unpredictability to an extent [13], their actual use in disaster planning is not so widespread.

Further, due to their low probability, HILO disasters often receive less attention and resources in disaster risk management planning [14]. Decision-makers may not prioritize them, since the opportunity cost of preparing for a rare event might seem too high compared to immediate, compelling needs – as exemplified by the Sri Lankan statistics above for the 2004 Indian Ocean tsunami, compared to those from other recurrent disasters in that country. Furthermore, investing significant resources into preparing for events that may never occur could be seen as inefficient [3]. This results in insufficient funding for HILO disaster preparedness and mitigation strategies [15]. Even if a plan is created, maintaining readiness over long periods of years or decades without the disaster actually occurring can be costly and difficult to justify. Equipment can become outdated, skills can deteriorate, and societies may become more complacent over time regarding such disasters. Further, unlike recurrent events for which communities may adapt gradually, HILO disasters produce disruptions that strain governance systems, infrastructure, and institutional learning [16].

Fujita and Yamashiki [3] argue that it is essential to find appropriate mechanisms to compensate for the damage and losses created due to HILOs, in order to increase future preparedness for them. Etkin, Mamuji, and Clarke [14] too state that adequate preparation for rare disasters is important, in order to ensure that sufficient attention is paid to mitigation and prevention strategies. Further, Mamuji and Etkin [17] state that the similarity assumed for low-probability/high-consequence events and high probability/low-consequence events in risk matrices is misleading, arguing that rare disasters should be analysed based on a systems perspective and given more importance, since any lack of preparedness for such events could elevate the impacts. As unfolded later in this paper, preparedness for HILO disasters would typically include education and drills. In addition to the disaster-specific preparedness that would be enhanced by these measures, they could also instil a proactive safety culture in populations – something that would serve them well not only for facing such HILO disasters, but also disasters in general.

We argue therefore that our focus on HILO disasters is strongly warranted because (i) their impacts (including death tolls) are very high in spite of their infrequent nature; (ii) they are increasing in frequency as well, partly due to climate change; (iii) they are difficult to predict and prepare for, not only because of their low probability but also due to the cascading effects they cause, fuelled by the complexity of the modern world [18]; (iv) they are typically soft-pedalled in disaster planning because of the pressing needs generated by more recurrent disasters; while (v) preparing for them (especially via education and drills) could enhance a safety culture that would serve populations well against all disasters.

We study such HILO disasters through a cross-category analysis of these disasters across several different categories, since such cross-category analyses are sparse in the literature. For example, Kappes et al. [19] do consider a variety of *causes*, but say nothing about the quality of institutions or governance when ascertaining risk. Galindo and Batta [20] focus on the various disaster *phases* in describing disaster operations management, but do not qualify it by variations in *context*. Calang [21] does compare the *contexts* of Japan and the Philippines, but only for the preparedness and response *phases*. Then Hallegatte et al. [22] analyse socioeconomic resilience (which can be treated as a *sector*) over 90 country contexts but only for disasters caused by floods; and Adger [23] discusses vulnerability using *dimensions* of adaptive capacity, governance and equity, but does not differentiate across other categories. Some recent studies however, constitute a move towards cross-category analyses. For example, Tierney [24] examines the social, political and economic *dimensions* of disaster governance in a variety of country *contexts* across multiple *hazards* and *phases*. Similarly, Hochrainer-Stigler et al. [25] propose a systemic risk framework by considering multiple interacting *hazards* for the infrastructure, economy, water and agriculture *sectors*; and analysing governance and socio-economics *dimensions* using regional and global case studies. Our own work seeks to extend this type of cross-category analysis, while also deliberately naming it as such.

Our first category relates to *causes*; and we look at disasters arising from geophysical, technological, biological and sociological causes in a variety of country contexts - with a focus on Asia, since the data was obtained under the auspices of the Association of Academies and Societies of Science in Asia (AASSA). The second category refers to *phases* of a disaster; and we investigate preparedness, response and recovery for such HILO disasters. The third category can be labelled as *dimensions* of analysis, cutting across both the above categories, key examples of which are socio-economics, governance and equity. In this process we look at differences introduced by *context*, since the data for the HILO disasters emanated from six different countries (making country context our fourth category). We also recognize that such disasters influence and are influenced by many *sectors* (our fifth category), such as health, education, infrastructure (including transport and utilities) and the economy. The aim of this paper is to advance disaster risk reduction by examining how diverse types of High Impact–Low Occurrence (HILO) disasters across different country contexts are prepared for, responded to, and recovered from under conditions of rarity and extreme uncertainty. As will be demonstrated later, the analysis of case studies via cross-category integration is important because it generates important insights regarding the unfolding of disasters in order to plan for them in future.

2. Literature review

2.1. Cross-category analysis of High Impact–Low Occurrence (HILO) disasters

This literature review examines the cross-category implications of HILO disasters, drawing insights from various academic sources, including and especially those from Asia.

The fundamental planning dilemma for HILO disasters is established by scholars [e.g. 3], who note their incompatibility with static, probabilistic risk frameworks designed for more frequent events. This issue is critically important because, as ref. [14] demonstrates, the impacts of HILO events are not contained but cascade dynamically across health, infrastructure, and economic sectors, creating compound crises. Therefore, the central scholarly debate would need to shift to appropriate response paradigms – for example, towards building strong and responsive institutions for disaster management, which is more effective than improving prediction accuracy [26].

The cross-sector impact of HILO disasters is evident across multiple sectors, including health, infrastructure, and the economy. For instance, a study by Rawat et al. [27] highlights the cascading effects of an earthquake in Nepal, where damage to infrastructure led to public health crises and economic downturns. The interconnectedness of sectors means that a disaster affecting one area can exacerbate vulnerabilities in others, necessitating a holistic approach to disaster risk reduction. Asia, being particularly vulnerable to HILO disasters because of widespread resource constraints, provides critical case studies that illustrate the complexities involved. The 2004 Indian Ocean tsunami serves as an important example - while the disaster was catastrophic in general, the recovery phase revealed disparities in resilience across different sectors [28,29].

The existing studies referred to below have reported that effective disaster recovery requires not only immediate humanitarian assistance but also long-term strategies that address underlying vulnerabilities in health, housing, and livelihoods. These studies also reveal various themes related to the cross-category analysis of HILO disasters, such as their frequency versus severity, prediction methods, preparedness levels, resource allocation, social capital, adaptive capacities, governance structures, equity, investment in disaster preparedness, and community-based preparedness strategies.

2.2. Prediction and preparedness for HILO disasters

The distinction between the frequency and severity of HILO disasters is crucial for understanding their impacts. While these events are infrequent, their severity can lead to catastrophic outcomes. The historical analysis of disaster data shows that rarer events often result in disproportionately higher damages and fatalities compared to more frequent but less severe ones [30]. This paradox highlights the need for a nuanced understanding of risk, as preparedness efforts often focus on frequent, lower-impact events, thus neglecting the severe consequences of HILO disasters.

Predicting HILO disasters poses significant challenges due to their low occurrence rates. Traditional predictive models may fall short in capturing the complexity and unpredictability of such events [3–5]. Recent advancements in machine learning and data analytics have shown promise in improving predictive capabilities. For instance, research by Kossin et al. [31] emphasizes the use of climate models to analyse patterns and enhance predictions for extreme weather events that could be precursors to HILO disasters. However, integrating these models into practical frameworks remains a challenge.

In addition, preparedness levels for HILO disasters vary widely across countries, and are often inadequate. Studies indicate that many regions, particularly in developing countries, lack comprehensive preparedness plans for rare events [32]. Furthermore, the effectiveness of preparedness measures is contingent upon community involvement and the integration of local knowledge [33].

Community-based preparedness strategies have proven effective in enhancing resilience to HILO disasters. Studies by Marsh et al. [34] highlight the importance of involving local communities in disaster risk reduction planning and implementation. Community-driven initiatives foster ownership and accountability, leading to more effective preparedness measures. Additionally, research suggests that local knowledge and practices should be integrated into formal disaster management frameworks, in order to enhance their relevance and effectiveness.

Preparing for HILO disasters requires extensive and comprehensive planning, involving scenarios that may not be fully imagined. For example, planning for a pandemic would involve healthcare systems, economic measures, global supply chains, and public communication strategies. Further, since HILO disasters are rare, it is hard to test preparedness plans in real-world situations. Simulations may not fully capture the chaotic and large-scale nature of such disasters, leading to unforeseen gaps in readiness when the event occurs. The Indian Ocean Wave (IOWave) simulations, conducted every two to three years, can be cited as a good effort in the right direction [35].

2.3. Social and institutional dimensions of HILO disasters

Pre-existing social capital significantly influences resilience levels during HILO disasters. Research by Aldrich [36] highlights that communities with strong social networks and cohesion are better equipped to respond to and recover from such events. Adaptive capacities, defined as the ability to adjust to potential damage, are enhanced through community engagement and collective action. In other words, measures for building local solidarity in communities can enhance or even substitute for social capital [37]. However, both social capital and governance structures are required for coping with disasters, and the literature suggests that the latter may be more important [38]. In other words, institutional breakdown can amplify disaster impacts beyond the coping capacity of communities [39]; and such breakdowns would be likely in high impact events. For example, the Fukushima disaster demonstrated that even in the highly cohesive Japanese society that has strong community networks, the catastrophe escalated because there were institutional shortcomings in the regulation, risk management, and crisis response within the government and plant operator [40]. Also, while recognizing the importance of both social and institutional factors, Alfano and Ercolano [41] suggest that the latter was more important for the success of COVID-19 lockdown effectiveness in Italy.

So effective governance structures are essential for managing HILO disasters. Studies indicate that decentralized governance models often lead to more responsive disaster management strategies [42]; also that collaborative governance arrangements can enhance communication and coordination among various sectors, improving disaster preparedness and response [12]. However, the effectiveness of these structures depends on the inclusivity of decision-making processes and the integration of gender perspectives [12]. In addition, decentralization can be critiqued due to concerns over coordination failures, differences between local governments and inequitable resource distribution in fragmented systems [43]. A judicious mix of centralized and decentralized approaches may be called for [44].

Equity is also a crucial consideration in disaster management, particularly with respect to HILO events. Vulnerable populations often bear the brunt of disaster impacts due to systemic inequalities. Research by Cutter et al. [45] argues that equitable resource distribution and targeted support for marginalized groups are essential for building resilience. Furthermore, incorporating equity into disaster risk reduction frameworks can lead to more effective and just outcomes [45].

2.4. Investment and awareness

Investment in disaster preparedness and response is vital for mitigating the impacts of HILO disasters. Studies show that proactive investment in infrastructure, early warning systems, and community training significantly reduce vulnerability [46]. Hallegatte et al. [23] emphasise the importance of investing in disaster risk reduction as a cost-effective strategy for minimizing future losses. However, many governments allocate insufficient resources to preparedness, often prioritizing immediate response over long-term resilience [23].

Maintaining awareness of HILO risks is crucial for effective disaster management. Public awareness campaigns and education initiatives play a significant role in enhancing community preparedness. A comparative analysis of typhoon responses in the Philippines and Japan demonstrates how preparedness measures can differ significantly based on historical experiences and institutional frameworks [22]. In the Philippines, the lack of infrastructure and early warning systems amplified the effects of HILO disasters [22], while Japan's rigorous building codes and disaster preparedness initiatives mitigated impacts [42]. Research indicates that informed communities are better equipped to respond to HILO disasters, as they understand the risks and appropriate response measures. Continuous risk communication and community engagement are necessary to sustain awareness and preparedness levels.

Resource allocation is a critical factor in mitigating the impacts of HILO disasters. Insufficient funding often leads to inadequate infrastructure, emergency response systems, and community preparedness initiatives [5]. According to UNDRR [2], effective resource allocation must prioritize vulnerable communities to enhance resilience. However, the challenge lies in balancing immediate response needs with long-term investments in disaster risk reduction.

From the risk perception perspective of the general public, HILO disasters attract less attention due to their lower frequency and visibility. Therefore, even from individual perspectives, communities are less motivated to plan and invest in preparing for them, since their low frequency does not translate to lived experience. Bechtel and Mannino [15] suggest however that greater information sharing could increase motivation.

2.5. Some gaps and debates

In concluding this literature review, we can state that there are studies on a variety of HILO disasters, covering different causes, such as volcanic eruptions [12], climate disasters [47] and pandemics [48]; and sectors such as power systems [49] and supply chains [50]. However, the existing literature is largely fragmented, typically focusing on isolated causes, disaster phases or sectors, with limited attention to cross-cutting dimensions such as equity and governance or to variations across country contexts. This fragmentation has important conceptual consequences. The impacts of and recovery from HILO disasters emerge from interactions between causes, disaster phases, sectors, governance arrangements, and country contexts, rather than from any single category in isolation. As a result, analyses that treat these categories separately risk overlooking key mechanisms that shape vulnerability, resilience, and the distribution of impacts. Accordingly, our paper addresses this gap by adopting an integrative framework that simultaneously considers disaster causes, disaster phases, cross-cutting dimensions (e.g. equity and governance), different sectors, and multiple country contexts, enabling a more holistic understanding of HILO disasters.

We have also identified some debates within the literature. An important debate for example, is one between an older paradigm that characterizes disasters by event intensity [e.g. 19]; and an emerging one which considers that social resilience and institutional capacity are as or more important for predicting disaster outcome [24–26]. There is a sub-debate within this as to whether social resilience or institutional capacity is more important, with some authors arguing for the former [36,45]; and others the latter [38,39]. The other important debate is the one between the view that prior experience of disasters is a key component for preparedness [e.g. 22]; as opposed to the growing realization that the direct experience of HILO disasters may be limited if not non-existent because of their infrequent occurrence [e.g. 15]. Our findings will shed some light on these debates, and can be seen as empirical evidence for choosing between the differing positions taken in the literature.

3. Methodology

This research employs a multiple case study design. The study of different risks across these case studies is not an attempt to employ multi-risk frameworks [e.g. 25]. Rather, as outlined by Yin [51], multiple case studies are a powerful means to provide compelling evidence when cases are carefully selected to predict contrasting results for anticipated reasons, thereby extending theoretical insights. In line with this principle, the study's examination of five different HILO disasters across six countries functions as a form of theoretical replication, where each case serves as a distinct unit of analysis that tests and refines the emerging understanding of disaster risk reduction measures, stakeholder responses, and contextual influences [51]. This approach allows for an in-depth, cross-contextual examination where findings from one case inform the analysis of others, thereby building a more comprehensive exploration regarding HILO disaster management than a single case study or a set of similar case studies would permit. In addition, our cross-category approach would greatly enhance this theoretical replication approach, since we are looking not merely at different contexts, but also at various causes, phases, sectors and dimensions.

3.1. Data collection

This study adopts a mixed-methods, multi-stage design in which the different methods are used in a complementary and integrated manner. The multiple methods employed are integrated within the overarching multiple case study design to ensure triangulation and depth. The documentary reviews and standardized questionnaires serve as the primary data sources within each case, with the former providing verified contextual and chronological data on the disasters and the latter capturing expert insights on processes and stakeholder actions [51]. The subsequent expert discussions functioned as a form of focus group to critique and synthesize preliminary findings across cases, thereby enhancing validity. Finally, summative content analysis was applied uniformly to the qualitative data from all sources, allowing themes identified in the literature review and questionnaires to be systematically compared across the cases to generate the replicable findings central to the theoretical replication logic [52].

A comprehensive literature review was first carried out to review the nature of HILO disasters and their differing categories. Next, case studies for different types of HILO disasters that occurred in the recent past were conducted, followed by discussion among case study participants, who were the experts from their respective countries. According to Robert Yin (see Ref. [53]), case studies are more appropriate to investigate contemporary situations - in our case investigating the disaster risk reduction measures during the lifecycle of a HILO disaster, the way different stakeholders respond, and implications of existing strategies; also how the phenomenon (i.e. a given HILO disaster in our case) and the context (i.e. specific country contexts in our case) create their own influences. The use of case studies for this study provided the overarching analytical structure and enabled in-depth examination of HILO disasters across different contexts. Accordingly, five different HILO disasters that occurred within six countries were evaluated through these case studies.

Within the case studies, there were two data collection methods used, namely a documentary review (described in Section 4.1 under each HILO disaster concerned); and a standardised set of questions completed by an expert, who was a nominee (i.e. Fellow) of six academies of science in Asia, each on the identified HILO disaster in their own country. The Indian contributor was from an autonomous government agency and the Indonesian one from the Indonesian Academy itself; while all others were university academics; and this suggests a relatively high degree of intellectual independence in the responses. In addition to their disciplinary training (i.e. structural engineering, geology, seismology, microbiology and building technology), all of them had some research and/or administrative experience in disaster studies.

Documentary reviews enabled the systematic identification of disaster characteristics, phases, sectors, and cross-cutting dimensions of HILO disasters. A standardized template comprising 21 key questions covering pre-disaster, mid-disaster and post-disaster phases pertinent to the HILO disasters was administered to the six country experts (see Supplementary Material: Part 1), facilitating the collection of comprehensive data regarding the specific HILO disasters examined in this study, and to capture comparable insights from key stakeholders across cases. It is important to note that the questions in the template were derived from the themes that emerged during the literature review described in the earlier section; however, other relevant topics were also included in the questionnaire – see Supplementary Material: Part 1. Adopting a qualitative research approach, the responses from the experts were initially entered into an Excel spreadsheet for systematic organization. Subsequent analysis was conducted using a summative content analysis method, which is characterized by its methodological rigor. Supplementary Material: Part 2 also demonstrates how themes from the literature review and questionnaire were continued in the Cross-Event Analysis (Section 4.2) and/or Discussion (Lessons and Strategies in Section 5.1).

Preliminary findings were presented at a three-day regional workshop that convened approximately 40 disaster-related country experts and stakeholders. A dedicated session during the workshop facilitated focus group discussions, enabling participants to generate insights within three areas, namely: analytical categories, lessons learned from the events, and strategies for resilience. The focus group discussions served to contextualize and interpret the findings, allowing for the exploration of interactions, divergences, and underlying mechanisms for HILO disaster management. This paper ultimately emerges from the synthesis of both the template analysis and the focus group discussions conducted during the workshop. In addition, some insights were gleaned from the keynote speakers at the HILO disaster workshop as well.

In the main, these methods enabled triangulation across data sources by systematically cross-validating findings from documentary evidence, stakeholder questionnaires, and focus group discussions within each case study. At the same time, the use of standardised instruments and a common analytical framework across cases ensured cross-case comparability. Further, qualitative methods provided contextual depth by capturing local dynamics, sectoral interdependencies, and governance and equity considerations that are not readily observable through documentary analysis alone.

3.2. Data analysis

Qualitative analysis encompasses a systematic process of reduction, while summative content analysis aims to identify significant components within the text and evaluate its overall implications [54]. Within this framework, the term "essential text" refers to elements within the data that illuminate the overarching meaning and significance of the findings. Essential text components may include contextual information, personal experiences, and emotional narratives, as outlined by Rapport [55].

In the examination of the HILO disaster data (i.e. the questionnaire responses), thematic analysis was used as the data analysis method. This involves a meticulous comparison of similarities, differences, and lessons learned from each study context, allowing for a comprehensive understanding of the phenomena under investigation [56]. Accordingly, the study first generated codes, which were subsequently developed into relevant themes (and a few sub-themes – see Supplementary Material: Part 3). The codes, themes (and sub-themes) generated within each case study were compared with the other case studies. It should be noted that the questionnaire itself (see Supplementary Material: Part 1) was organized on the basis of themes generated from the literature review (see Supplementary Material: Part 2). Therefore, we could say that the themes were generated in both top down fashion (from the literature review) and in bottom up fashion (from codes arising out of the questionnaire responses).

In concluding this section, we acknowledge some methodological limitations, such as the reliance on just a single expert for each of the case studies (with their inherent biases and foci of expertise); and the potential subjectivity arising from our qualitative synthesis. We suggest that the triangulation of our findings with the literature, and their moderation via the focus group discussions, could compensate somewhat for such limitations.

Table 1
The six HILO disasters considered.

Academy	HILO disaster	Cause/Trigger	GDP (PPP) - USD
National Academy of Sciences of Sri Lanka	2004 tsunami in Sri Lanka	geophysical	12,200
Science Council of Japan	2011 Tohoku earthquake, tsunami; plus Fukushima	technological	41,838
Indian National Science Academy	2013 Kedarnath Glacier Lake Outburst Flood	geophysical	7,112
Nepal Academy of Science and Technology	COVID-19 pandemic in Nepal	biological	4,002
Indonesian Academy of Sciences	COVID-19 from Indonesian perspective	biological	12,410
Bangladesh Academy of Sciences	Rohingya refugee influx into Cox's Bazaar	sociological	6,263

4. Findings and analysis

4.1. Case study descriptions: specific HILO disasters

This section provides an overview of six country-specific HILO disasters selected for this study – see also Table 1. Note that the inputs for the analysis were provided by representatives of the six academies of science indicated, under the auspices of the Association of Academies and Societies of Science in Asia (AASSA), with coordination carried out by the National Academy of Sciences of Sri Lanka (NASSL). The table highlights the variety of HILO disaster types (causes) covered and also gives the per capita GDP (on a PPP basis) for the countries concerned; the latter can be considered a very rough quantitative index of context. Note that there is a clear gap between the index that corresponds to Japan and those of the other countries.

The first case study is the Indian Ocean tsunami of 2004 in Sri Lanka. This catastrophic event occurred on December 26, 2004, and impacted numerous countries surrounding the Indian Ocean, with Indonesia being the most severely affected, followed by Sri Lanka to a lesser yet significant extent. The tsunami was triggered by a massive submarine earthquake, which struck approximately 400 km west of northern Sumatra at around 6:30 a.m. Sri Lanka time. The earthquake registered a magnitude of 9.3 on the Richter Scale, with a fault length exceeding 1000 km. The tsunami reached Sri Lanka's eastern coast at approximately 8:30 a.m. and its western coast by 9:30 a.m., affecting over two-thirds of the nation's 1400 km coastline [28,29,57]. The disaster resulted in the deaths of approximately 40,000 individuals and the destruction or damage of around 120,000 houses. The direct economic losses related to assets and infrastructure were estimated at nearly US$ 1.0 billion, with total losses approximating US$ 2.2 billion. The housing sector experienced the most significant asset loss, estimated between US$ 306 and 341 million [58]. Although resumption of education activities and restoration of rail, road and telecommunication networks was completed within 6 months, housing and school reconstruction took 5 years or more; and some business recovery over 10 years.

The second case study focuses on the 2011 Great East Japan Earthquake and the Fukushima Nuclear Power Station accident. On March 11, 2011, a massive earthquake with a magnitude of 9.0 struck off the coast of Tohoku, Japan, generating a devastating tsunami. This earthquake was the largest recorded in Japanese history and the fourth largest globally. It resulted in nearly 20,000 casualties, predominantly due to the ensuing tsunamis. More significantly, the tsunami inflicted extensive damage to the Fukushima Dai-ichi Nuclear Power Station, leading to reactor meltdowns, hydrogen explosions, and the release of radioactive materials [42,59,60]. The recovery from the tsunami damage took many years, but was almost complete in just over a decade. However, the recovery from radioactive pollution still continues after more than a decade.

The third case study examines the Glacial Lake Outburst Floods (GLOF) in Kedarnath, Uttarakhand, India, in 2013. From June 14 to 17, 2013, the intense flash floods that occurred emerged as one of the most catastrophic disasters for India since the 2004 Indian Ocean tsunami, posing significant challenges for rescue operations. The floods were precipitated by unprecedented rainfall, rapid melting of snow and glaciers in the upper reaches, and the subsequent filling and breaching of the moraine-dammed Chorabari Lake. The sudden and immense outburst of water, laden with debris and boulders, surged down the steep slopes, devastating villages such as Gauri Kund, Ram Bada, and Sonprayag in the Kedarnath region. This deluge, compounded by landslides, resulted in approximately 6000 fatalities with hundreds reported missing, inundated 5500 villages, and stranded over 100,000 pilgrims and tourists during the peak summer season. According to ecologist Chandra Prakash Kala, the estimated financial losses included US$ 285 million in damage to bridges and roads, US$ 30 million for dam repairs, and US$ 195 million from impacts on state tourism [61–63]. Long-term rehabilitation is still not complete over a decade after the event.

The fourth case is the COVID-19 Pandemic in Nepal (January 2020 to October 2022). The COVID-19 pandemic, caused by the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2), had significant health and economic repercussions globally. In Nepal, the first case of COVID-19 was reported on January 24, 2020 in a student returning from China, with a subsequent case identified approximately two months later in an individual returning from France. A complete genome sequence of the SARS-CoV-2 strain from a Nepalese patient exhibited a 99.6% identity with the reference genome. Notably, a majority of reported COVID-19 cases were asymptomatic. During the early stages of the pandemic, the potential for an outbreak in Nepal was considerably underestimated; however, there was a marked increase in cases over time, highlighting the challenges faced in managing the pandemic response [64]. In all, Nepal experienced around 250,000 cases and 12,000 deaths [65].

The fifth case is the COVID-19 Pandemic in Indonesia (January 2020 to December 2022). Indonesia reported its first confirmed cases of COVID-19 at the beginning of March 2020, with two cases identified. By April, the country recorded 1790 confirmed cases, including 113 new cases, 170 deaths, and 112 recoveries. As the threat of COVID-19 became apparent, the Indonesian government implemented various policies to address the crisis, including the designation of 100 domestic general hospitals as Referral Hospitals (Rumah Sakit Rujukan) in March 2020, a number that increased to 227 within a month. Nevertheless, despite these measures, the number of cases continued to rise rapidly. The Ministry of Health of Indonesia established a website to provide real-time data on the various impacts of COVID-19 within the country [66–68]. Indonesia recorded some 6.8 million cases of COVID-19, with around 160,000 deaths. In both Nepal and Indonesia, although some response cum recovery was completed in 6 months, recovery in terms of economic development continues to date, over 5 years after the event.

The sixth case is the Rohingya refugee influx on the groundwater system of Cox's Bazar region in Bangladesh and the ensuing social conflicts. The influx of refugees into Bangladesh began on August 25, 2017, following military operations by the Myanmar Army in northern Rakhine State. During the period from August to November 2017, over 750,000 forcibly displaced Myanmar nationals of Rohingya ethnicity fled to Bangladesh, joining earlier waves of Rohingya refugees who had sought asylum in the 1970s and 1990s. Currently, nearly one million Rohingya refugees reside in Bangladesh, predominantly in the Cox's Bazar district, near the Myanmar border [69,70]. This sudden influx exerted immense pressure on the local host community and its already strained facilities and services. Initially, the local population extended support and assistance to the newcomers; however, over time, the host communities' immediate sympathy waned due to increasing pressure on land, forest, and groundwater resources. The arrival of Rohingya refugees has indeed strained natural resources, particularly in the Cox's Bazar region, raising concerns about potential conflicts arising from resource competition [71]. So the high impact arose from both the social conflict and pressure on natural resource depletion; and the interactions between them. Some aspects of the recovery were completed within 6 months, such as putting up camps, registering the refugees, providing humanitarian assistance, improvising water, sanitation and hygiene (WASH) facilities, providing medical care facilities and setting up schools. However, many of these still continue over 5 years after the event, along with other recovery responses, such as avoiding conflicts with local communities; reducing pressure on shared resources such as land, fuelwood and groundwater; and increasing resilience to landslides.

These selected HILO disasters encompass a range of events, including geophysical disasters (tsunamis, earthquakes, floods), biological disasters (COVID 19 pandemic) and a sociological disaster (refugee influx). The Indian Ocean tsunami and the Kedarnath GLOF are classified as disasters resulting from geophysical processes, while the COVID-19 pandemic in Nepal and Indonesia represents a public health crisis with extensive socio-economic implications. The Rohingya refugee influx in Bangladesh exemplifies a humanitarian crisis, resulting from geopolitical conflicts and environmental factors. The Fukushima event could be called a technological disaster, triggered by a geophysical hazard. While this diversity necessitates tailored response strategies that account for the unique characteristics and impacts of each HILO event, there are generalizations for HILO disasters that can be made as well.

4.2. Cross-Event Analysis

While this analysis is structured with respect to the *phases* of a HILO disaster (preparedness, response, recovery), embedded within are *themes* (see Supplementary Material: Parts 2 and 3) such as prediction, awareness, community resilience, governance, equity and investment, with examples from our case studies. These themes also recur (as generalized lessons and strategies) in the Discussion, within Section 5.1.

4.2.1. Preparedness: awareness, knowledge and experience of the HILO events

The study findings suggest that a lack of awareness of the risk prior to HILO disasters, underestimation of disaster risks, and lack of effective preparedness and capacity of governments, experts and people, coupled with the scale and suddenness of the disaster event, contributed towards the high impact of these disasters. In addition, disasters such as the Indian Ocean tsunami, Fukushima nuclear power station accident, and the influx of Rohingya refugees were not adequately recognized as risks, primarily due to their infrequent occurrence. In Sri Lanka, for instance, there was a complete lack of awareness regarding the tsunami risk among all parties. However, Japan stood out as an exception with respect to its preparedness for the Great East tsunami and ensuing Fukushima nuclear power plant accident, although certain policy measures were not effectively implemented at the local level. It should be noted that Japan experiences frequent tsunamis (unlike Sri Lanka), but certainly not nuclear accidents. Recall also that Japan has by far the highest GDP per capita compared to the other contexts explored (see Table 1) – so levels of preparedness may well be connected to those of economic prosperity.

Maintaining awareness of HILO event risks is essential for effective disaster management [72]. In Sri Lanka, the tsunami increased public consciousness about disaster preparedness, leading to community engagement initiatives. Japan's experience with the 2011 disasters has fostered a culture of preparedness, although complacency remains a concern. The Kedarnath GLOF underscored the need for greater public awareness of climate change impacts. During the COVID-19 pandemic, both Indonesia and Nepal faced challenges in maintaining public consciousness about health risks, consequently impacting response efforts. In Bangladesh, the ongoing Rohingya crisis has raised awareness among officials and the public about the complexities of humanitarian responses, although local communities still require more support and education on the issue.

4.2.2. Responses to HILO disasters

The research data includes the diverse actions undertaken by governments during the response phase of the HILO disaster. For instance, during the Rohingya refugee influx, the Bangladesh government permitted Rohingyas to seek refuge across the border, providing essential security, food, and emergency medical services. Also, the relevant governments concerned established relief camps to offer shelter, sustenance and medical aid to affected individuals as an initial emergency response to the Indian Ocean tsunami, Fukushima nuclear accident and Glacial Lake Outburst flood. Similarly, in response to the COVID-19 pandemic, both the Nepalese and Indonesian governments implemented various measures such as endorsing universal personal protection, enforcing physical distancing, and imposing localized lockdowns, travel restrictions, isolation protocols, and selective quarantines. Across these responses, a critical aspect observed was the strengthening of governance structures and institutional capacity, including the development of coordinated emergency management protocols, the establishment of clear lines of authority, and the enhancement of public service delivery systems to improve response effectiveness for future HILO events. For example, Sri Lanka's Disaster Management Act and Disaster Management Centre (DMC) came into existence just one year after the 2004 tsunami. It is this DMC which now monitors all disasters in the country and is responsible for responses to such disasters. In addition, where HILO events such as tsunamis are concerned, it coordinates an annual time of silence on the anniversary of the 2004 Boxing Day tsunami; and also the IOWave exercises [72]. This underscores the importance of institutions for preparedness and awareness promotion. It is now 20 years since the tsunami event in Sri Lanka. So while school children have no experiential knowledge of the same, their participation in drills, coordinated by a dedicated disaster related institution, probably gives them some degree of awareness and preparedness.

However, a consistent feature observed across all HILO disasters examined in this study was the active involvement of civil society in response efforts as well. In India for example, numerous civil society organizations played a pivotal role in delivering humanitarian aid and relief services to affected communities. Volunteers participated in rescue operations, distributed essential supplies such as food and medical assistance, and organized temporary shelters. Community groups and religious organizations effectively managed resources and extended support to impacted families, coordinating relief initiatives and addressing the immediate needs of vulnerable populations. In fact, the active engagement of civil society entities across all these HILO disasters underscored their crucial role in facilitating response and recovery processes, showcasing resilience and solidarity in times of crisis.

Parallel to the responses from formal civil society groups, the general public also played a significant role across various HILO disasters. In Sri Lanka for example, individuals offered emergency shelter, transportation, food and clothing to those affected by the disaster. Remarkable frontline work was carried out, with the Ministry of Health establishing a network of safe houses through local initiatives to provide affected individuals with shelter, sustenance, and accommodation. The unique response dynamics underscores the diverse approaches taken by communities in different disaster scenarios, highlighting the importance of both coordinated efforts and adaptive context-based strategies to effectively address the challenges posed by HILO disasters. Further, these community and civil society group activities underscore the importance of coordinated governance and adaptive community engagement, highlighting how investments in institutional capacity and governance frameworks could enhance immediate response. One significant difference in the COVID-19 HILO disasters was that civil society and the general public were both constrained and restrained in their responses, due to the contagious nature of the pandemic that afflicted those affected.

4.2.3. Recovery phases in HILO disasters

All HILO disasters were characterised by immediate relief efforts from governments, civil society, and the unaffected general public. Nonetheless, it is noted that the return to normalcy often extended over long periods of time due to the high-impact nature of these disasters. While the Indian Ocean tsunami of 2004 highlighted the effectiveness of immediate aid responses in Sri Lanka, some aspects of recovery took over 10 years. In the context of the Fukushima Nuclear Power Station accident, long-term recovery and rebuilding efforts faced challenges in gauging the opinions and consensus of residents. In the Glacial Lake Outburst Floods, the efficacy of recovery efforts was enhanced by well-coordinated initiatives that involved government agencies, civil society actors, and international partners. During the COVID-19 pandemic in Nepal, the effectiveness of recovery initiatives in facilitating a return to normalcy similarly depended on an uninterrupted transition from emergency relief to long-term recovery efforts. In comparison to other epidemic and endemic conditions, the return to normalcy during the COVID-19 pandemic was protracted due to the novel nature of the disease and the absence of an established cure. Various trial methods were employed to address the health crisis, including traditional, ayurvedic, and allopathic approaches. In Indonesia, effective collaboration between the government and local communities demonstrated greater efficacy in recovery efforts. In the Rohingya refugee influx, a multi-tiered response involving government and local communities, non-governmental organizations (NGOs), civil society actors, and (later on) international organizations effectively provided humanitarian services to a substantial number of individuals.

These extended recovery periods highlight limitations in institutional capacity, especially in sustaining recovery momentum, coordinating multi-sectoral interventions, and managing cascading and long-duration impacts. In addition, analysis suggests that in most instances, post-disaster recovery measures have contributed to the exacerbation of existing socio-economic disparities within local contexts rather than diminishing them. One of the features of the pandemic, for example, was the relatively long disruptions to education, as a result of the prioritization of social distancing [73]. Although online education was resorted to as a response to this, such education delivery tended to increase inequities within populations, since rural poor communities were not equipped to benefit from it.

These social disparities may be intensified, especially if vulnerable communities slide into poverty; hence the dimension of equity must be carefully monitored through the various phases of HILO disasters, especially in the recovery of the economic sector. For example, the Rohingya refugee influx in Bangladesh exacerbated existing inequalities, as local communities faced increased competition for resources, leading to tensions and potential conflicts. Japan's robust disaster response mechanisms provided a more equitable recovery for affected populations, yet disparities persisted in the long-term impacts of the Fukushima disaster.

This study also noted the active participation of the international community in disaster relief and post-recovery efforts, with the notable exception of the Rohingya refugee influx. Reports indicate that the international response was delayed in this context, primarily due to the complexities of the human, social and political dynamics involved. This study illustrates the variability of within-country recovery responses, highlighting the different levels of involvement from national and local governments, NGOs, and grassroots communities in disaster recovery efforts. Collectively, these findings underscore that effective recovery from HILO disasters depends not only on short-term response capacity but also on long-term institutional capacity building, governance arrangements that integrate risk into development planning, and deliberate efforts to improve social equity to prevent the disproportionate burden of recovery from falling on already vulnerable populations.

The data gleaned for this study indicated that the Indian Ocean tsunami in 2004, the Fukushima Nuclear Power Station accident, the COVID-19 pandemic in Indonesia, and the Rohingya refugee influx were characterized by a rather centralized governance approach. In contrast, the responses to the Glacial Lake Outburst Floods and the COVID-19 pandemic in Nepal were supposedly more decentralized. In particular, while the Nepalese government reportedly adopted a decentralized approach during the COVID-19 pandemic, the Indonesian government apparently maintained a centralized one. These centralized or decentralized approaches of relevant governments could perhaps impinge on decisions related to mitigation and preventive measures. However, with the exception of the nuclear power station accident, the other HILO disasters examined in this research encountered difficulties in securing adequate future investments due to their infrequent nature, leading to lacunae in establishing preventive measures.

In concluding this analysis, we argue that it is our cross-category analysis that has generated insights such as the one that Japan's generally good performance in the Fukushima disaster may be linked largely to its *context* of having a much higher GDP per capita. Also, that while HILO disasters may create a 'levelling' effect across all social strata (in that most people are affected by them during the disaster *phase*), differences in the equity *dimension* tend to arise in the recovery *phase,* especially in the economic *sector*. Or again, that disasters due to biological *causes* may result in the education *sector* being disproportionately affected, while also stifling community efforts in the response *phase*, perhaps causing the governance *dimension* to become more centralized. It is clear therefore that single category analyses are insufficient for exploring (especially HILO) disasters. In fact, it is cross-category interactions such as the above that could even define whether or not an event constitutes a disaster. Such analyses also shed light on the actual interaction mechanisms – e.g. disasters due to biological *causes* require social distancing in the response *phase*, which disrupts the education *sector* (among others); while attempts by (say centralized) governance to mitigate this via online teaching could reduce equity among the population since poorer segments would not be equipped to participate (note: here both governance and equity are *dimensions*).

5. Discussion

The discussion incorporates lessons and strategies that can be identified through the analysis of five major HILO disasters in six different contexts (see Table 1), supplemented by insights from the HILO workshop held in Colombo Sri Lanka in September 2024. The lessons were gleaned largely from the template analysis; and the strategies from the workshop focus group. They cover, in different ways and degrees, all the categories of HILO disasters we set out to study – namely causes, phases, dimensions, contexts and sectors. In addition, this discussion also sets our findings in the context of existing disaster theories, while also challenging and extending some of them.

5.1. Lessons and strategies

The findings demonstrate that experiential learning alone is insufficient for managing HILO disasters, as limited historical exposure constrains systematic learning and preparedness. Instead, the results highlight the importance of anticipatory and scenario-based planning, especially in contexts where HILO disaster risks are poorly understood or socially discounted. The existing science communication associated with all the disasters covered in this study indicated shortcomings, emphasizing the need for rapid dissemination. In fact, the findings of this study underscore the necessity for well-developed early warning systems to which science communication is integral, both during and after High Impact Low Occurrence (HILO) disaster events. This system should cater not only to the disaster-specific needs but also to the socio-economic and cultural considerations unique to each context.

While geological events like earthquakes can be somewhat anticipated, climatic ones such as glacial lake outburst floods (GLOFs) are often unpredictable. The case of the Kedarnath GLOF in 2013 exemplifies this unpredictability, as rapid glacial melting led to catastrophic flooding with little warning [63]. Hence, in addition to scenario-based analysis and predictive modelling before such disasters, robust surveillance systems and enhanced monitoring technologies are required during the unfolding of these extreme events. This can only be done by the strengthening of institutions via training and investments in technology.

Equity is a crucial consideration in disaster management, since disparities in access to resources and support systems often exacerbate vulnerabilities among marginalized populations [3,14,15,45]. This concern is particularly salient in the context of HILO disasters, where the rare but extreme nature of events can amplify pre-existing social and economic inequalities. It should be noted that although macroeconomic indicators such as GDP could return to trend just a few years after these HILO disasters, segments of the population that slide into poverty could take generations to recover; the recommended mitigation measures are cash handouts and livelihood generation [74].

Governance plays a vital role in shaping the response and recovery efforts for HILO disasters. Empirical investigations indicate that the effectiveness of disaster management is determined by coordination, transparency, accountability, and resource allocation, consistent with risk governance and institutional capacity frameworks, which emphasise how institutional arrangements and governance processes influence the ability to manage complex risks [12,26,42,75]. This was validated by the findings of this study, as the countries with strong governance took efficient and effective measures during the aftermath of the HILO disaster. Conversely, inadequate governance can lead to poor management, as seen in the Rohingya crisis, where resource allocation and support systems were insufficient.

Investment in disaster preparedness and response is crucial for mitigating the impacts of HILO disasters [3,14,15]. Empirical investigation indicates that sustained investment in disaster risk reduction, healthcare systems, and emergency infrastructure enhances the capacity to absorb shocks and recover effectively, while gaps in investment exacerbate vulnerability and amplify the impacts of rare, high-consequence events. These findings align with resilience and risk governance theories [26,76], which highlight that proactive, sustained, and equitable investment is essential for mitigating the long-term consequences of HILO disasters and ensuring adaptive capacity in affected communities.

The reluctance to make investments to prepare for HILO disasters was evident in all contexts explored, perhaps apart from the case of Japan. One alternative to structural investments could be to increase awareness through education and drills. The Indian Ocean Wave (IOWave) exercise for the relatively rare tsunamis in the Indian Ocean, conducted every few years, are a good example of region wide preparedness, with elements of the exercise reaching down to the 'last mile' category as well [72]. The notion of drills for preparing against pandemics (involving short duration shutdowns) was surfaced at the workshop, but no consensus was arrived at regarding the feasibility or mechanisms for the same.

HILO disaster theory suggests that preparedness cannot rely on experiential learning alone, as the infrequent occurrence of such events limit opportunities for systematic learning from past disasters [77]. The findings of this study empirically support this proposition, indicating that preparedness levels for HILO disasters vary significantly across regions, reflecting differences in institutional capacity, organisational learning, and governance maturity. Developing Standard operating Procedures (SoPs) and institutional frameworks for disaster risk reduction [12,42]; establishing community-based preparedness programs [26]; and improving access to information can enhance readiness in vulnerable areas. According to Satake [42] and Lee [12], well-established institutional frameworks would clearly identify the stakeholders and agencies that need to be worked with during a disaster. In addition, the information flow, e.g. with regard to issuing early warnings, should also be identified [12,42]. Such guidelines will facilitate timely response and recovery measures.

One of the greatest assets for facing HILO disasters is the social capital built up in countries (e.g. through education) that produces resilience, especially in the response phase. Such strengthening of local communities appears to be a priority for preparedness, especially given that such community responses played a significant role in many of the HILO disasters studied. One corollary that follows from this is that efforts should be made to reduce disruptions to education (which contributes significantly to such social capital) that could occur in disasters caused by pandemics (which tend to call for social distancing).

Resilience is a critical factor in determining how communities withstand and recover from HILO disasters, and is consistent with adaptive capacity theories. According to these theories, pre-existing social capital, adaptive capacities, and community cohesion shape the ability of communities to absorb shocks, reorganise, and recover after extreme events. The empirical evidence from this study (i.e. that communities with strong social networks are better equipped to respond to crises, mobilise resources, and adapt to changing conditions), reinforces theoretical assertions that resilience emerges not solely from physical infrastructure but from the interaction of social, institutional, and ecological capacities [26].

Raising awareness about HILO disasters among officials and the public is important for improving preparedness and response strategies. Continuous education and training programs can foster a culture of resilience and vigilance. For instance, community workshops and simulation exercises can enhance public understanding of risks and appropriate responses, thereby improving overall resilience. In addition, participation in drills would significantly increase awareness.

While social capital, resilience, and disaster education are well established as fundamental components of disaster risk management, their role within the context of HILO disasters requires specialised adaptation. The infrequent occurrence of these events makes it difficult for communities and institutions to rely on recent experience, thus weakening risk perception, collective memory, and preparedness motivation over time. For this reason, strategies for social capital enhancement in HILO settings require mechanisms that preserve inter-generational knowledge, institutional continuity, and community-based early-response networks even during extended periods without observable risk.

To strengthen preparedness for HILO disasters, it is essential to embed long-term and recurring institutional mechanisms rather than relying on event-driven learning. Alongside this, institutional memory audits and leadership briefings should be periodically undertaken to ensure that key lessons, operating procedures, and response roles remain current despite administrative turnover. Furthermore, integrating disaster preparedness requirements into statutory planning cycles ensures that preparedness activities are systematically reviewed, budgeted for, and operationalised within broader development and governance frameworks. Together, these measures provide continuity, reinforce institutional capacity, and reduce the risk of knowledge erosion over extended periods without disaster occurrence.

The study highlights the need for strategies that enhance resilience against High Impact–Low Occurrence (HILO) disasters. Strengthening community-based preparedness, local training programs, emergency response teams, and early warning systems can improve readiness, while inclusive governance, effective institutions and equitable resource allocation ensure that vulnerable populations are supported. Investment in resilient infrastructure and advanced monitoring technologies further reduces disaster impacts. Fostering public awareness and engagement cultivates a proactive culture of resilience. Overall, the findings underscore the interconnections between resilience, governance, equity, investment, and public consciousness, demonstrating that integrated, theory-driven strategies are essential for effective preparedness, response, and recovery in the face of rare but catastrophic events.

5.2. Theoretical contributions

The findings both extend and challenge the existing HILO literature in several important ways. First, while prior HILO studies largely emphasise rarity, hazard characteristics, and probabilistic risk assessment, this study extends the literature by demonstrating that institutional capacity, governance quality, and social resilience are decisive determinants of outcomes in HILO events. The findings show that the consequences of rare, high-impact disasters cannot be explained by hazard magnitude alone, but are strongly shaped by how preparedness, coordination, and decision-making are institutionalised prior to the event.

Second, the study challenges dominant assumptions that learning and preparedness primarily evolve through repeated experience. Given the infrequent nature of HILO disasters, the findings reveal that experiential learning is insufficient, and that effective preparedness depends instead on anticipatory planning, scenario-based training, and institutionalised memory, for example as in the case of Japan.

This aligns with HILO disaster theory, which challenges conventional disaster risk models that prioritize event frequency and instead emphasizes extreme impact potential under conditions of rarity [77]. Further, by integrating perspectives on extreme risk, uncertainty, governance, and equity, the study reframes HILO disasters as systemic stress tests that expose latent vulnerabilities and inequalities, thereby advancing HILO theory beyond event-centred and frequency-driven interpretations toward a more governance- and resilience-oriented understanding. Hence, we advance the theoretical proposition that managing HILO risks requires scenario-based preparedness and predictive modelling that are capable of operating under profound uncertainty to improve forecasting capabilities for such unpredictable disasters. Much greater use could be made, for example, of futures studies, which did in fact gain some traction during the COVID-19 pandemic [13].

The findings further suggest that conventional risk models based primarily on event frequency are inadequate for HILO disasters. Instead, risk frameworks need to prioritize impact severity, worst-case scenarios, and deep uncertainty, recognizing that rare events can dominate overall losses and societal disruption. This supports a shift from prediction-centred approaches toward scenario-based planning and anticipatory risk management, where preparedness is designed for extreme consequences rather than historical likelihood. In addition, the study has implications for governance and resilience models, demonstrating that effective management of HILO disasters depends on institutional capacity, inclusive governance, and social resilience, rather than infrastructure or response speed alone. Resilience models should therefore integrate social capital, equity, and institutionalised preparedness, while governance frameworks should emphasise coordination, accountability, and adaptive decision-making under uncertainty. Together, these findings highlight the need for integrated risk–governance–resilience models capable of addressing the systemic and unequal impacts of rare but catastrophic events.

By integrating risk, governance, and resilience perspectives, this study explains why similar HILO events produce divergent impacts and recovery trajectories, thereby extending HILO theory from event-specific analysis to a more comprehensive, socially grounded framework for understanding HILO disasters. Hence, we advocate for advancing the HILO disaster literature beyond hazard-centric and frequency-based interpretations toward a systemic understanding of rare, high-impact events as critical tests of risk governance, institutional capacity, and social resilience.

6. Conclusions

The study of five different HILO disasters in six different country contexts constituted a theoretical replication approach that enabled some common features of such disasters to be arrived at, especially given that it was studied across the multiple categories of causes (geophysical, technological, biological, sociological), phases (preparedness, response, recovery), dimensions (e.g. socio-economics, governance, equity), contexts (six countries with varying GDPs), and sectors (e.g. health, education, infrastructure, economy).

The study highlighted the importance of (i) scenario-based (worst-case) analyses rather than probabilistic ones for HILO disasters, perhaps using futures analyses; (ii) mechanisms that preserve inter-generational knowledge, institutional continuity, and community-based early-response networks even during extended periods without observable risk; (iii) strengthening both institutional capacity and community resilience; (iv) ensuring equity, especially in the recovery stages of HILO disasters; and (v) making appropriate investments for increasing preparedness, if not through structural interventions, at least through sustained awareness programs and periodic drills.

The study findings can also be seen as making some key theoretical contributions. For example, while prior HILO studies largely emphasise rarity, hazard characteristics, and probabilistic risk assessment, this study demonstrated that institutional capacity, governance quality, and social resilience are decisive determinants of outcomes in HILO events. Second, the study challenged dominant assumptions that learning and preparedness primarily evolve through repeated experience; arguing rather that scenario-based training and institutionalised memory need to be relied upon for these rare events. Finally, by integrating perspectives on extreme risk, uncertainty, governance, and equity, the study reframed HILO disasters as systemic stress tests that expose latent vulnerabilities and inequalities, thereby advancing HILO theory beyond event-centred and frequency-driven interpretations toward a more governance- and resilience-oriented understanding.

CRediT authorship contribution statement

Unnathi Samaraweera: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Udayangani Kulatunga:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Priyan Dias:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no competing interests where this paper is concerned.

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(Economist, School of Oriental and African Studies, University of London), Dilanthi Amaratunga (Global Disaster Resilience Centre, University of Huddersfield) and Senaka Basnayake (Asian Disaster Preparedness Centre, Thailand).

Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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