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Continuing from the Sendai Framework midterm: Opportunities for urban digital twins in disaster risk management

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Abstract

Urban areas and cities face risks caused by the compounding impacts of urbanization and increasing frequency of disasters. The importance of implementing disaster risk management integrated with strategies to achieve sustainable urban development is highlighted by the United Nations Office for Disaster Risk Reduction (UNDRR) through the Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR), which provides guidelines for monitoring and reporting the implementation of disaster risk reduction strategies towards resilience and sustainability. In this paper, we present a systematic review of the studies on urban disaster risk management since the Sendai Framework's adoption in 2015 until 2022—at its midterm—identifying implementation challenges that urban digital twins can possibly address. Our study involved two stages. First, a scoping review looked at the profile of journal articles and their research trends on the topic. Second, 141 publications were selected for full-text review and synthesis within the context of the Sendai Framework priorities of action. In these studies, research on urban resilience has gained increased attention, but the importance of risk assessment is still highlighted as one of the critical process of disaster risk management. Overall, the reviewed studies reveal the complexity of disaster risk and management—requiring research considerations in different facets of: multi-dimension, multi-scale, multi-stakeholder, multi-hazard, and multi-perspective. Research directions show opportunities for urban

digital twins in disaster risk management—particularly, as the integrating framework and platform of urban systems and disaster risk management processes.

Keywords: urban resilience, sustainable development, SDG, literature review, UNDRR

1. Introduction

Across the globe, urban areas and cities are at the center of social and economic life, and are threatened to be disrupted by the increasing frequency of disasters [1, 2]. A rise in the number of urban disasters has been noted especially in tropical areas where many developing countries are located, and in the report *Human cost of disasters* of the UN Office for Disaster Risk Reduction (UNDRR), the overview of the disaster risk reduction within the years 2000 to 2019 show the sharp increase in number of disaster events—with 7,348 disaster events recorded from 4,212 in years 1980 to 1999 [3]. This situation is further impacted by climate change: increasing the frequency and extent of hazards and extreme events, which are expected to pose additional challenges to achieving sustainable development [4], with higher costs to people and assets anticipated [5]. For example, in coastal cities, hazards (e.g. sea-level rise, storm surges, and floods) may potentially increase due to climate change and threaten both population and infrastructure [6]; or in the case of urban pluvial floods, people may be displaced and their livelihood impacted, and infrastructure damaged [7]—adding relevance and emphasis to the consideration of integrated and improved disaster risk management systems as an essential element in sustainable development [8, 5].

The United Nations (UN) estimates that around 68% of the world's population will be living in cities by 2050 as urbanization of cities continue—which would mean increasing number of people who may be exposed to urban disaster risks. Well planned urbanization have positive impacts to the three dimensions of sustainable development, i.e. economic, societal and environmental [9]; On the other hand, unplanned or unmonitored urbanization puts the urban areas and its population at risk of experiencing socioeconomic inequalities, environmental impacts and unsustainable developments

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Sustainability can be seen as humanity's target goal, reached through sustainable development [11]. In the post 2015 developmental agenda setting of the UN, the Sustainable Development Goals for 2030 (SDGs)—also called the Agenda 2030 or the global goals—were presented and adopted to anticipate these risks and promote sustainable development [12]. For urban areas, the SDG 11 in particular has the goal to make *"cities and human settlements inclusive, safe, resilient and sustainable"* with SDG Target 11.5 specifically aiming to assess the reduction of disaster impact [10].

Alongside the SDGs, the Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR), or simply the Sendai Framework, was officially adopted as guide to the implementation of targets in disaster risk reduction and management [13], with the UNDRR leading the the global efforts to address disaster impacts and risks. Year 2020 was intended to mark the 5-year milestones for progress on the SDGs and Sendai Framework, however, the covid-19 pandemic brought about an unexpected disaster previously not experienced in recent years [14], which exposed many shortcomings in disaster risk management and the need for a systemic and multi-hazard approach [3]. Further, inherent to the objective of disaster risk management is the reduction of risk while promoting sustainable development, which lead to promoting 'resilience'.

Resilience emerges as new research paradigm of urban safety [2] and the end goal of disaster risk management—through the successful reduction of the disaster risks in a community, and achieving the sustainable development targets. In this view, resilience as a mindset can be realized by achieving the 'inverse of risk' [11]. As such, the importance of disaster risk reduction in order to achieve sustainable development is paramount [15]; however risk-informed planning strategies and disaster preparedness are still limited [16].

Previous systematic reviews have looked into general topics such as investigating progress in urban resilience research [17] and setting of roadmap and research agenda in multi-hazard risk assessment [18, 19]; while others have narrowed down to a specific focus topic, such as on urban flood risk and mitigation strategies [7], assessing the preparedness for the disasters [5], or assessing risks at large gatherings [20]. In our review, we are particularly interested to discover research directions towards the use of digital technologies to support urban disaster risk management and support its implementation, specifically through identifying related characteristics of urban digital twins.

In recent years, the 'digitalization' of cities or the concept of the 'digital city' emerged through the developments and advancement in information and communications technology (ICT) industry, alongside advances in digi-

tal technologies—seen as an inevitable and logical direction of city modeling and moving towards the 'future city' paradigm for applications in the urban and built environment [21, 22]. This direction of the current digital transformation of cities is seen with the developments in and implementation of smart city technologies and urban digital twin (UDT) concepts towards sustainable and resilient cities [21], which promoted developments in disaster risk management [6]—such as a 'smart city' as an integrated system of interconnected critical infrastructures to realize strategies for disaster resilience [23].

Implementations of urban digital twins are still in developmental stage and are the focus of on-going researches regarding its aspects or components and challenges [24, 25, 26, 27]. Considering the complex scope of urban disaster risk management, the need for implementing of frameworks that capture its multi-faceted characteristics—in perspectives, scale, detail, and dimensions—present an opportunity for urban digital twin implementation through capability to integrate digital city datasets with simulation models and machine learning algorithms that assist in developing 'smart' systems, for supporting the different processes across the disaster risk management cycle of a city.

In this paper, we seek to understand the status of the adoption and implementation of the Sendai Framework based on the body of peer reviewed literature and revisit its progress in the context of sustainable and resilient cities — we present a systematic literature review on the progress of research from articles published from 2015 up to the end of 2022 on the topic of urban disaster risk management. As envisioned platforms for implementing integrated sustainable development and disaster resiliency, an investigation on opportunities for urban digital twin development was also done to identify gaps and future research agenda. As the aim of this review is to provide an evaluation of the progress, we look into answering the following research questions:

RQ1: What have been the key research trends on the topic of urban disaster risk management?

RQ2: What studies have been carried out in relation to the implementation of the Sendai Framework?

RQ3: What are the research gaps and directions for disaster risk management, and how can urban digital twins be used to support them?

The rest of the paper are organized as follows: in Section 2, we give further background and context to disaster risk management, the Sendai

Framework and related concepts; this is followed by the review design and screening criteria discussion in Section 3; the results in each review stage are presented in Section 4, followed by the discussion and review synthesis in Section 5; we present our identified research directions for urban digital twin implementation in Section 6 and conclude the paper in Section 7.

2. Background and related concepts

In this section, we provide additional context and overview of the disaster risk concepts and processes, and background on digital technologies implemented for urban disaster risk management. Table 1 provides the adopted definitions for disaster risk terms from the UNDRR Terminology[1].

2.1. Disaster and risk concepts

The terms 'disaster' and 'hazard' have been used interchangeably, but as defined by UNDRR the former is the disruptive outcome from the impact of the latter. Seemingly a minor nuance, however proper differentiation adds clarity to the processes in disaster management, e.g. disaster risk assessment and hazard risk assessment though similar would require different considerations in implementation. On the concept of 'disaster risk', it is basically a measure of the disruption caused by a hazard event and quantified through the process 'disaster risk assessment'. In general, the processes in disaster risk assessments include: (i) Identification of hazards—a review of the technical characteristics of hazards such as their location, intensity, frequency and probability; (ii) Analysis of exposure and vulnerability—including the physical, social, health, environmental and economic dimensions; and (iii) Evaluation of the effectiveness of prevailing and alternative coping capacities with respect to likely risk scenario.

Risk assessment is at the core of risk management [28], and could either involve all or focus on just one of the process. In previous years, the focus was on 'disaster management' which focused on actions to restore normalcy after a hazardous event. However, in recent studies, the focus has already shifted to disaster risk management [18], giving emphasis on the risks [18]—which lead to urban resilience research [17, 29]. 'Disaster risk management' is the process of implementing 'disaster risk reduction' strategies, especially towards managing risk. In general, the key stages of risk management that can be identified based on its definition are: (i) Prevent new disaster risk,

[1] `https://www.undrr.org/terminology`

Table 1: Definitions of disaster risk and management related terms.

Term	**Definition**
Disaster	A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts.
Hazard	The process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.
Disaster management	The organization, planning and application of measures preparing for, responding to and recovering from disasters.
Disaster risk assessment	A qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend.
Resilience	The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.

(ii) Reduce existing risk, (iii) Manage residual risk, and (iv) Strengthen resilience.

In the urban context, the fragility of the built environment and the accompanying social vulnerability are revealed during disasters, but could be assessed before the disaster through appropriate risk assessment [30]. This interplay of managing risk and risk reduction as described by Chen et al. [28] can be analyzed as: (i) inherent risk, obtained from risk assessment resulting from hazard and vulnerability indicators; (ii) residual risk, the risk that remains after some risk prevention or mitigation measures—which needs to be continuously controlled by risk management measures; and (iii) new risk, which is from reassessment after emergency situations have ended [28]. The cycle repeats until an 'acceptable' risk is possible, which is expected to lead to achieving a reasonable degree of safety and security, and likewise resiliency.

2.2. Sendai Framework for Disaster Risk Reduction and the New Urban Agenda

The Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR)—officially endorsed by United Nations member states at the Third UN World Conference in Sendai, Japan on March 18, 2015—is the successor to the Hyogo Framework for Action 2005-2015 and complements the other 2030 Agenda agreements. It builds on the lessons and challenges identified from the Hyogo Framework, identifying the shift to a stronger emphasis on disaster risk management rather than only on disaster management, and broadening the scope to focus on multi-hazards, both natural and man-made, encompassing environmental, technological and biological hazards and risks [13].

It has been seven years since the adoption of the Sendai Framework, and now moving past halfway through its planned 15-year implementation period, the UN General Assembly has concluded its midterm review, conducted in conjunction with the other global agenda, i.e. SDGs—best practices and issues towards better solutions to disaster risk and related sustainable development identified. The report on the midterm review of the Sendai Framework was presented during the UN General Assembly on May 2023, describing the progress of its implementation based on the voluntary national reports of member states [31].

Among the guiding principles of the Sendai Framework is on disaster risk reduction which has a requirement of shared responsibilities of relevant stakeholders (e.g. national governments, authorities and sectors) and all-of-society engagement and partnership, which would depend on available co-

ordination mechanisms and empowering policies—leading to a multi-hazard approach and risk-informed decision making. Disaster risk reduction is acknowledged as essential to sustainable development, and addressing disaster risk would be more cost-effective than primary reliance on post-disaster response and recovery [13].

To achieve its overall goal of preventing new and reducing existing disaster risk, the Sendai Framework recommends the implementation of integrated and inclusive measures—economic, structural, legal, social, health, cultural, educational, environmental, technological, political and institutional—that can prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness for response and recovery, and thus strengthen resilience. It outlines recommended guidelines for implementing disaster risk reduction into sustainable development, and how to protect development gains from the risk of disaster. In this paper, we contextualize our review of urban disaster risk research on the framework's 4 priorities of action described briefly below (see [13] for full descriptions):

Priority 1: Understanding disaster risk. Understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment.

Priority 2: Strengthening disaster risk governance to manage disaster risk. Disaster risk governance at the national, regional and global levels for an effective and efficient management of disaster risk. Strengthening disaster risk governance for prevention, mitigation, preparedness, response, recovery and rehabilitation.

Priority 3: Investing in disaster risk reduction for resilience. Public and private investment in disaster risk prevention and reduction through structural and non-structural measures; to save lives, prevent and reduce losses and ensure effective recovery and rehabilitation.

Priority 4: Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction. Strengthen disaster preparedness for response, take action in anticipation of events, integrate disaster risk reduction in response preparedness and ensure that capacities are in place for effective response and recovery at all levels; Empowering women and persons with disabilities; Opportunity to "Build Back

> Better", including through integrating disaster risk reduction into development measures, making nations and communities resilient to disasters.

Related to the SGD11 and specific to achieving the sustainable development goals in urban areas, the New Urban Agenda of the UN Human Settlements Programme (UN-Habitat) elaborates the guidelines towards well-planned and well-managed urbanization [32]. The handbook accompanying the UN-Habitat's 'Urban Agenda Platform'—an online global knowledge portal for sharing of resources related to the New Urban Agenda and urban SDGs [2]—presents the New Urban Agenda's design to present universally applicable long-term vision and priorities and actions, as well as tools to meet needs and challenges specific for the urban context within 4 core dimensions: Social sustainability, economic sustainability, environmental sustainability and spacial sustainability. In conjunction to related SDG targets, the handbook provided sample case studies to elaborate the underlying principles, concepts and illustrative actions, as well as the challenges that can be addressed.

One of the key information in the New Urban Agenda handbook is the guidelines for reporting, presented in documents as 4 elements that can support reporting process: (i) Data platforms and systems, (ii) Platforms for engagement, participation and collaboration, (iii) Partnerships with relevant entities of the UN system, and (iv) Capacities to report on data collection and analysis, implementation and stakeholder engagement. In the context of an urban digital twin implementation, these processes could be investigated and studied to identify how the conceptualization of the urban digital twin framework could be steered towards an enabling platform.

The UN-Habitat also presented the Global Urban Monitoring Framework (UMF), developed for the purpose of having an integrated assessment approach for the varied indices being used by different organizations in measuring city prosperity, sustainability and performance in specific city sectors (i.e. environmental sustainability, poverty and health), and other indices such as those particular to smart cities performance—revolving around 5 principles: (i) Draw on existing frameworks, (ii) Be people-centric, (iii) Be city-centric, (iv) Make it useable and useful, and (v) Monitor responses to current and future shocks—implemented towards 4 city objectives, to be: safe and peaceful, inclusive, resilient, and sustainable [33]. These principles

[2] https://www.urbanagendaplatform.org/

and objectives reflect the directions to possible UDT implementation.

2.3. Digital technologies for urban studies and disaster risk management

Studying the built environment and related urban processes have benefited from the developments of digital technologies [21, 34]. The utilization of geospatial datasets (i.e. satellite imagery, aerial photographs, geographic data vector layers) are essential for urban studies—and there are now many available software tools [35] that allow us to achieve improved understanding and discovery of urban characteristics, such as travel mobility patterns [36], public transportation accessibility [37], local climate zones and urban heat islands [38], urban morphology [39, 40] and urban growth of neighborhoods [41], to name a few. Likewise, computer vision methods have found relevance in the utilization of street view imagery to reconstruct 3D building models [42] and generate urban metrics, such as for pedestrian activities and mobility [43] and urban bikeability [44]. The growing number of artificial intelligence (AI) models have also furthered the applications in urban studies [45].

Urban technological solutions introduced the smart cities concept—describing the city that make use of information and communication technologies (ICT) for efficient data collection and at the same time for 'smart' decision-making [34]—as possible solution for sustainable urban development [46]. This concept has been adopted in different urban application domains, one of which is in disaster and risk management [23, 47, 6], which further develop towards research on urban resilience and promote adaptability and sustainable development through the creation of 'resilient cities' [17].

Recently, urban digital twins have emerged as the next technology for urban modeling and process simulations [21]—building upon previous implementations of smart cities and digital twins in other industries [48, 49, 50, 51, 27, 26]. Establishing common definitions and implementation of the urban digital twin concept are still the scope of current and developing research [48, 52, 49, 50, 51, 34, 27, 26], but a simplified understanding of the concept can be seen as a convergence of four urban digital technologies: spatial data infrastructure, urban models, smart city service and internet of things [53]. The urban digital twin can be thought of as a digital city model that "twins" the physical component of the city and its city systems, with the capability to interact with it through sensor technology [49, 54].

It is clear from recent studies on smart cities and urban digital twins that a common goal is utilize this technologies towards achieving transforming cities to sustainable and resilient cities. In the work of Schiavo & Magalhães (2022) [55], they posit that 'sustainable cities' could be considered as the

concept integrating the socio-cultural, economic, and environmental aspects of the city—thus the term 'sustainable cities' could be understood as an umbrella for other related concepts including the smart city, which aim to improve the sustainability of cities by the integration of technology and with stakeholder collaboration, incorporating different city themes. This argument promotes the idea that the digital transformation of cities, i.e. urban digital twins or smart cities enables urban sustainability.

The UDT may be implemented as a framework for simulation models that can be applied to several use cases in urban management areas—such as transport and traffic, energy, waste, water, building, climate action, and disaster—and its fast growing adoption call for finding the ways to translate concepts to implementation of UDTs [56]. Having no universal definition or a definitive 'blueprint' yet for UDTs, we envision urban digital technologies as the enablers of sustainable disaster risk management, thus in the scope of our review, we identify possible research directions of implementing an urban digital twin for disaster risk management based on identified use cases and characteristics an urban digital twin from literature, further discussed in Section 6.

3. Review design and criteria

We performed our review according to the practice in the field [20, 57, 7], conducted in in two stages and following the flow illustrated in Figure 1. We begin with literature search by topic (i.e. title, abstract and keyword tags) in the Web of Science (WoS) online database using the search query: *TS=((management OR reduction OR assessment) AND (sustainability OR sustainable OR resilience OR resiliency) AND urban AND disaster AND risk)*. The same search was performed in Scopus. The period covered is 2015-01-01—considering 2015 as the start year of the Sendai Framework—up to 2022-12-31, covering seven years in this review. The specific steps in each review stage are discussed in the succeeding subsections.

3.1. Review stage 1: Scoping review and preliminary analysis

Considering the broad scope of disaster risk management and inter-related concepts, we want to first get a general view of research conducted on the topic for an overall profile of the studies. In stage 1, starting from the resulting articles identified from the database search, non-English articles and duplicates were identified through reference manager software and manual assessment and removed. Book chapters, conference proceedings,

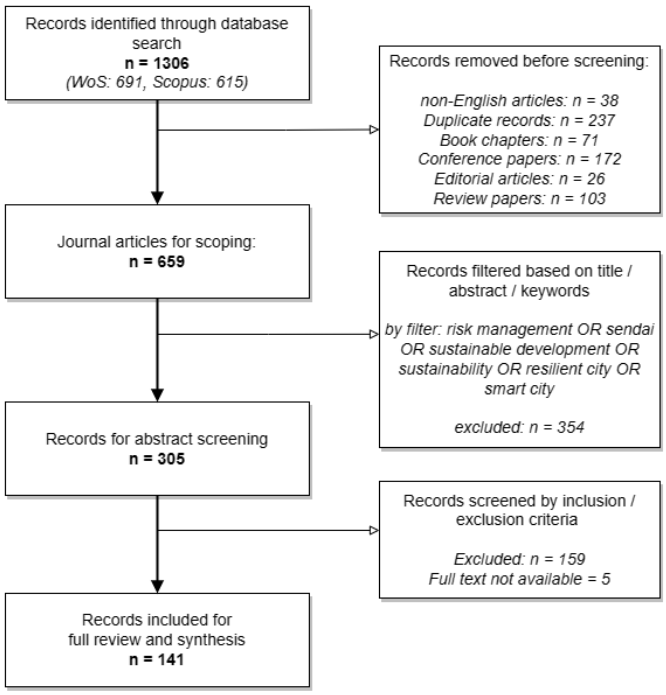


Figure 1: Review design and methodology followed for screening of articles.

editorial articles and review papers were also excluded to arrive at the article list for scoping. Visualization and analysis were done to look at the overall profile of the available studies, including: the number of publication on urban disaster risk management in the period covered, and top countries and journals with the highest number of published articles on the topic. We also looked at select topics of interest (shown in Table 2) which we used in a keyword search within the title, abstract and keyword tags to generate keyword co-occurrence graphs for analysis of topic convergences.

We categorized the articles into 9 representative topics based on the Sendai Framework's four priorities of action: these include three categories under Priority 1, one under Priority 2, two under Priority 3 and three under Priority 4, summarized in Table 3 with the description of the criteria used as basis for inclusion.

3.2. Review stage 2: Screening for final list of articles and categorization

In stage 2, we selected journal articles based on titles, abstracts and keyword tags by applying the query: *(risk management OR smart city OR*

Table 2: List of keywords queried on title, keyword tag and abstract for checking co-occurrence within the articles.

Build back better	Governance	Resiliency	Smart City
Climate Change	Hazard	Response	Sustainability
Community	Hyogo Framework	Risk	Sustainable Development Goal
Covid	Landslide	Risk assessment	Urban
Digital Twin	Management	Risk management	Vulnerability
Disaster	Mitigation	Risk reduction	
Exposure	Preparedness	SDG11	
GIS	Recovery	Sendai Framework	

sustainable OR sustainability OR resilience OR sendai framework) to get the articles on the topic of urban disaster risk management with specific context on sustainability, resiliency, smart cities and the Sendai Framework. The resulting articles were then screened and evaluated for full text review based on their abstract and scope using the inclusion criteria as follows:

- Include: Studies with scope related to the urban areas or cities
- Include: Studies covering any of the disaster management cycle phases (i.e. mitigation, preparedness, response, recovery)
- Include: Studies covering any of the disaster risk assessment components (i.e. vulnerability, hazard and impact assessment, adaptive capacity, risk analysis)
- Exclude: Studies focused on indoor environments (eg. indoor evacuation) or resilience of buildings, structure or cultural heritage sites
- Exclude: Studies focused only on hazards mapping or simulation

4. Results

This section presents the results from the 2 review stages discussed in Section 3. Discussion of synthesized review is done with perspective of the Sendai Framework based on emergent common research outcomes and themes. Research gaps were identified and possible future research directions converging with implementation of urban digital twins are presented in Section 5.

4.1. Profile of studies

From the literature search query we obtained n=1306 articles (WoS: n=691, Scopus: n=615). We removed non-English articles (n=38) and duplicates (n=237) and book chapters (n=71), conference papers (n-172), editorial articles (n=26) and review papers (n=103) to arrive at n=659 articles

Table 3: Representative categories derived from the four Sendai Framework priorities of action.

Sendai Framework	**Category**	**Inclusion criteria**
Priority 1	Risk assessment	Studies on assessing risk to disasters, including vulnerability assessment.
	Hazard assessment	Studies focused on mapping hazards, hazard simulation models and hazard susceptibility (risk).
	Impact assessment	Studies focused on measuring and identifying impact of hazard to people or structures.
Priority 2	Governance	Studies looking into the planning and regulations aspect of disaster risk, including financing, policy and institutional services.
Priority 3	Mitigation measures	Studies specific to developing strategies to reduce impact of disaster.
	Disaster management systems	Studies covering a more general view of disaster risk and management, especially focused on the system as whole.
Priority 4	Community-centric	Studies with particular focus on community engagement and participation, or approaching the analysis in the point of view of the locals, informal settlers, PWD or women, eg. incorporating local knowledge or household level of analysis.
	Preparedness	Studies analyzing disaster preparedness strategies, including translating lessons learned to anticipating and improving disaster preparedness.
	Resilience frameworks and models	Studies looking into disaster risk management holistically, and specifically implements resilience concepts. Also includes studies on measuring and assessing resiliency.

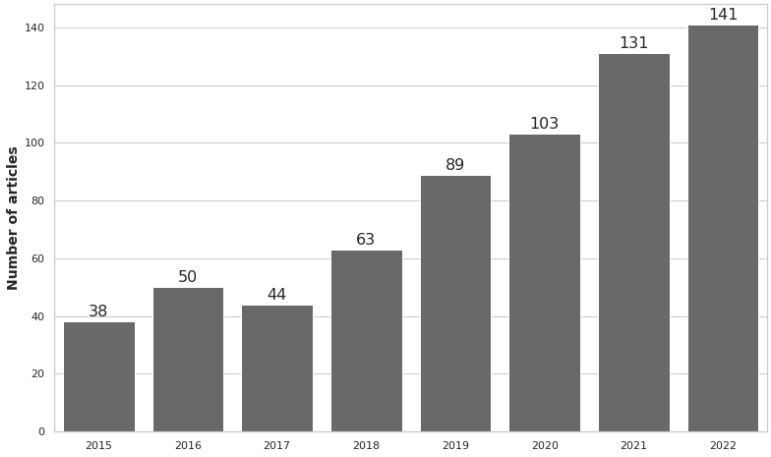


Figure 2: Number of published articles on the topic from 2015 to 2022, suggesting a surge in interest in this topic in the research community.

for the stage 1 article list. We generated several plots to look at the profile of studies on the overall scope of disaster risk management. The trend of publication per year is shown in Figure 2 and we can see the increase in number of published articles on the topic from 2015 to 2016, with slight drop in 2017 but continued to consistently increase up to 2022. This is a good evidence of the importance of disaster risk and at the same time an indication that there are still continued study on the topic because of the complexity and many facets of disaster risk management.

A keyword search within the article titles, abstracts and keyword tags was performed for different hazards, specifically: flood (or flooding), earthquake, landslide, tsunami, storm (or cyclone or hurricane or typhoon), storm surge and covid. From the resulting search, a plot of the keywords were generated to look at the trend of hazards studied or mentioned in the articles for the period covered, illustrated in Figure 3.

We can see from Figure 3 that researches about flood (or flooding) has the highest count (n=299), which is consistent with the statistics of the UNDRR report that flooding has the highest occurrence among the different natural hazards [3]. The emergence of the covid-19 pandemic is also reflected in the plot for the years 2019 to 2022, showing its impact to disaster risk research.

We looked at the top 10 countries with most number of articles published on the topic for the period covered, shown in the plot in Figure 4. It can be noted that China has the highest number of published articles on the topic,

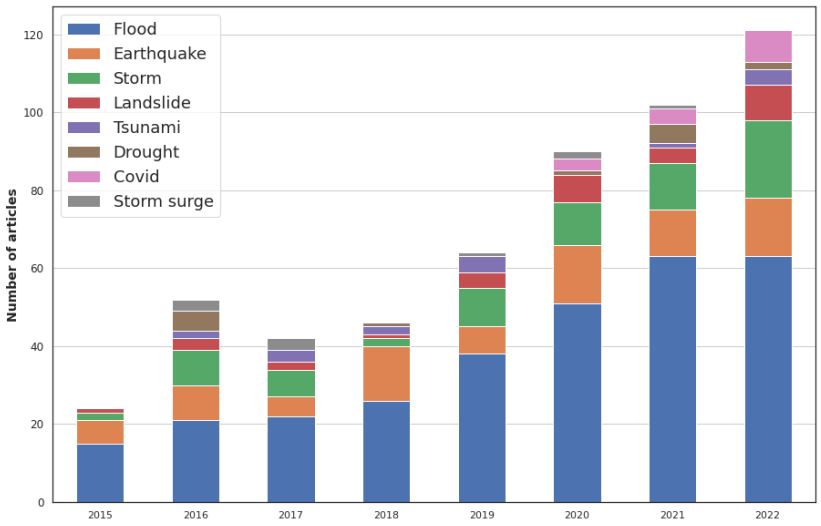


Figure 3: Trend of hazards studied and mentioned for period 2015 to 2022 indicates flood (flooding) as most occurring.

along with USA, UK, Italy and Germany. It may be worth mentioning that among the top 10 countries, only China and USA are in fact likewise the top 2 among the list of countries that had the most number of disaster events as described in the report of the UNDRR [3]. Conversely, the other countries with most number of disasters, such as Indonesia and Philippines, have a low number of published articles on disaster risk management (at 23rd and 25th respectively), indicating a need for these countries to promote continued studies on the topic.

Further, we identified the top 10 journals on number of articles published on the topic, summarized in Table 4. It is not surprising to find the most number of articles published are in the *International Journal of Disaster Risk Reduction*, which has focus scope on the topic and closely collaborating with the UNDRR. The other journals in the list are also to be expected because of the search keywords used in our database query, i.e. urban, disaster, risk and sustainability. The *International Journal of Environment Research and Public Health* has a fair number of articles published, especially due to the recent covid-19 pandemic—but also due to the relevance of disaster risk to concerns on public health.

4.2. Keyword co-occurrence graphs

Using the keywords listed in Table 2, the search within the article titles, abstracts and keyword tags produced a count of articles where these

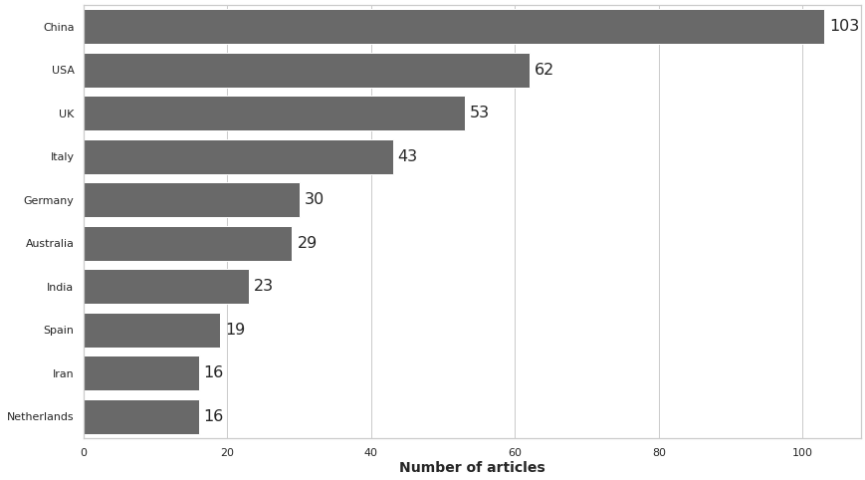


Figure 4: Top 10 countries with highest number of articles published related to urban disaster risk management within the studied period (2015 to 2022).

Table 4: Top 10 journals based on the number of articles published related to urban disaster risk management from 2015 to 2022.

No.	**Journal Name**	**No. of Articles**
1	International Journal of Disaster Risk Reduction	88
2	Sustainability	61
3	Natural Hazards	32
4	International Journal of Disaster Resilience in the Built Environment	27
5	International Journal of Environmental Research and Public Health	22
6	Water	16
7	Disaster Prevention and Management	13
8	International Journal of Disaster Risk Science	12
9	Cities	11
10	Environment and Urbanization	11

keywords occur and the count of of co-occurrence of each keyword pairs were generated. The co-occurrence graphs were created using the the online visualization tool Flourish [3]. The keyword co-occurrence graphs for all keyword-pairs is shown in Figure 5 and for select keywords shown in Figure 6, with the size of node circles representing the frequency of the keyword occurrence. There are a total of 284 keyword co-occurrence pairs as network

[3] `https://flourish.studio/`

edges (links) connecting the nodes, with the edge thickness representing the frequency of co-occurrence between pairs. Overall, the keywords *urban*, *disaster* and *risk* appear in all articles, which is are among the main keywords used in the literature search.

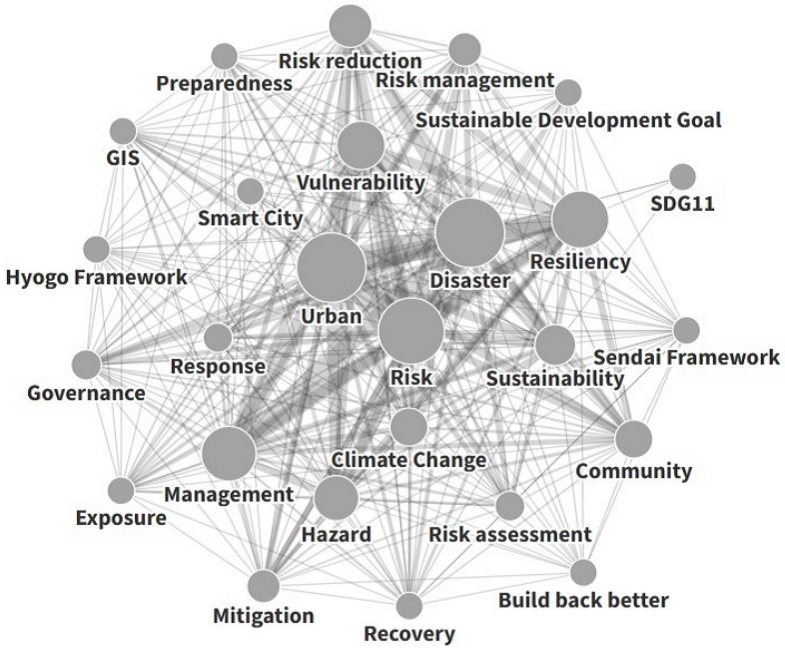


Figure 5: Co-occurrence graphs of all selected keywords

Among the keyword occurrence and co-occurrence pairs, of particular interest are the other frequent keywords which were not used in the literature search; for example the keyword *climate change* has frequency of 198—approximately 30% of the total number of articles in the scoping review—and co-occurred in 23 pairs. More notable is *vulnerability* (freq=321, 48%), which occurred among the next most frequent keywords *Risk, Resiliency* and *Management*, 598 (91%), 446 (68%), 412 (62%) occurrences respectively.

From the co-occurrence network graph, we can do visual analysis of separate views for different keywords and their co-occurrence pairs. Sample views are seen in Figures 6a to 6f, for the graphs of co-occurrence pairs with the selected keywords: *risk management* (freq.=123, 19%, co-occur.=22), *sustainability* (freq.=230, 35%, co-occur.=25), *sustainable development goal* (freq.=20, 3%, co-occur.=21), *Sendai Framework* (freq.=29,

4%, co-occur.=23), and *smart city* (freq.=7, 1%, co-occur.=13). For these specific keywords, it is of particular interest of the authors to note that the keyword *smart city* occurred very low, indicating still few studies on smart city with use case related to urban disaster risk management. Furthermore, there were no article in the list where the keyword *digital twin* occurred. We could already note this as indicative of possible research directions of implementing urban digital twins in disaster risk management.

The other keyword of importance in this study as mentioned previously is *Sendai Framework* for checking how many studies have implemented it or used it as guide. This keyword was present in only 29 articles out of the 659 (1% occurrence). A more accurate count of articles that explicitly mentioned the Sendai Framework was identified to be 47 out of the 141 papers in the full text review (33%). However, if we take this as the indicator of the number of times the framework has been explicitly implemented, this is relatively low (7% of the total 659 articles), considering the Sendai Framework is expected to be the guidelines in disaster risk reduction and management strategies.

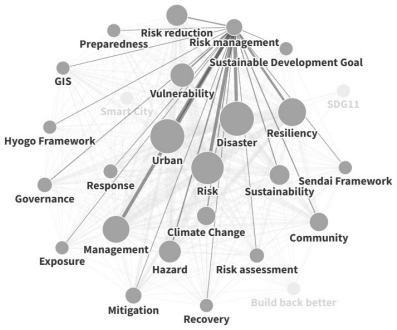
4.3. Categorized journal articles

Using the representative topics in Table 3, the number of articles as categorized are summarized in Table 5.

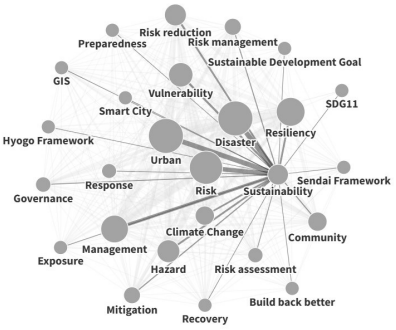
Table 5: Number of articles included in each category

Category	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Total**
Resilience framework and models	11	10	11	10	24	26	39	32	163
Disaster management systems	11	7	8	19	11	10	20	23	109
Risk assessment	2	8	7	9	7	17	26	21	97
Community-centric	6	8	7	10	13	18	12	14	88
Governance	5	7	7	7	17	12	5	14	74
Impact assessment	0	4	2	3	7	8	12	16	52
Hazard assessment	0	2	2	3	6	6	8	13	40
Mitigation measures	2	2	0	1	1	4	7	3	20
Preparedness	1	2	0	1	3	2	2	5	16
Year Total	**38**	**50**	**44**	**63**	**89**	**103**	**131**	**141**	**659**

Figure 7 shows a plot of the number of articles categorized under each review theme. The highest number is under the *Resilience frameworks and models* category, primarily because of the broad definition adopted in the screening process, but it is also because the emergent convergence of topics related to disaster risk management and sustainable development is resilience. Of particular attention as well is the low number of articles categorized under *Preparedness* and *Mitigation measures*. Although this might



(a) Co-occurrence with 'Risk management'

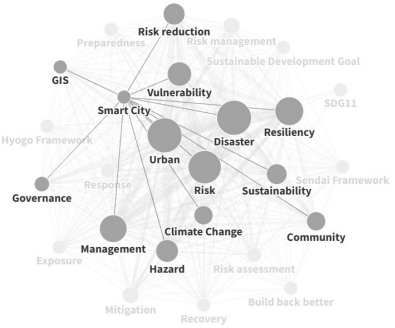


(b) Co-occurrence with 'Sustainability'

(c) Co-occurrence with 'Sustainable Development Goal'

(d) Co-occurrence with 'Sendai Framework'

(e) Co-occurrence with 'Vulnerability'



(f) Co-occurrence with 'Smart City'

Figure 6: Generated keyword co-occurrence graphs of keywords of interest. Larger node size indicate higher keyword occurrence. Similarly, thicker edges indicate higher frequency of keyword pair co-occurrence.

not completely capture the actual number of implementations studied in the

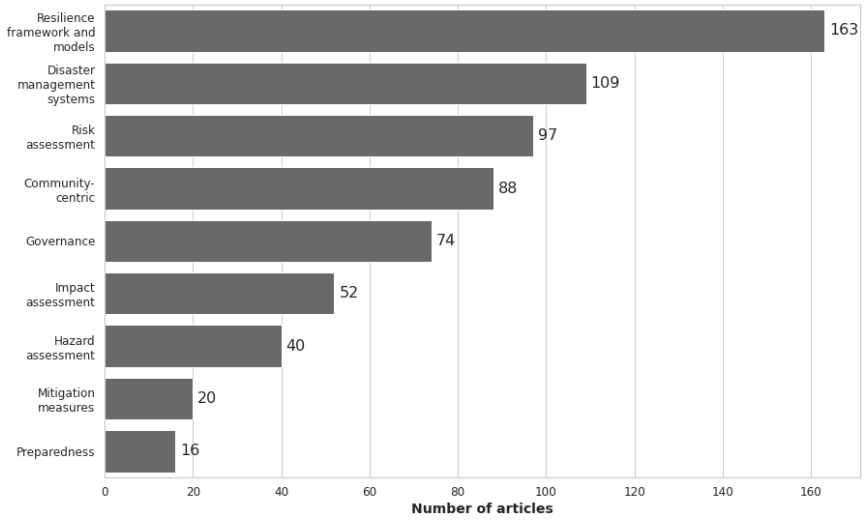


Figure 7: Number of articles categorized in each review theme.

articles—and this is not to say these two were not tackled in the articles under the other categories, such as in the papers under *Disaster Management Systems* or *Resilience Frameworks*—this indicates there has been low focus or difficulty on these components of disaster management among the current set of articles reviewed.

It should be noted that the the categorization of the studies are not meant to be definitive since in general all of the articles could belong to more than one of categories due to the complexity of the disaster risk reduction and management topic domain.

4.4. Final list of articles for synthesis

The final list of articles for full text review are summarized in Table 6 according to review theme categories, and we can note that there are 24 articles specifically mainly on the Sendai Framework Priority 1, 15 on Priority 2, 31 on Priority 3 and Priority 4 has the highest number, with 71 which is 50% of the total.

5. Discussion

From the review of the 141 articles in the final list (Table 6), we found several overall themes common among the studies and we present them in the succeeding subsections with our relevant findings in the context of the

Table 6: Final list of articles for full text review per representative category for the Sendai Framework priorities of action

SF Priority	Category	No. of articles	Papers
1	Risk assessment	15	Alizadeh et al. [58], Anhorn et al. [30], Assis Dias et al. [59], Carreño et al. [60], Chen et al. [28], Fakhruddin et al. [61], Feng et al. [62], Galderisi and Limongi [16], Koc and Işık [63], Patri et al. [64], Rana and Routray [65], Şenol Balaban [66], Su [67], Yang [68], Yenneti et al. [69]
	Hazard assessment	3	Franci et al. [70], Munpa et al. [71], Wu et al. [72]
	Impact assessment	6	Alkinani et al. [73], Boccard [74], Fraser et al. [75], Innis [76], Liu et al. [77], Moulds et al. [78]
2	Governance	15	Clark-Ginsberg et al. [79], Cui et al. [80], Dieperink et al. [81], Djalante and Lassa [82], Dwirahmadi et al. [83], Filippi [84], Gera [85], Handayani et al. [86], Hutter [87], Kelman and Clark-Ginsberg [88], MacAskill and Guthrie [89], Meyer and Auriacombe [90], Milanes et al. [91], Ruane et al. [92], Sun et al. [93]
3	Disaster management systems	29	Battegazzorre et al. [94], Busayo et al. [95], Caro-Camargo and Gil-Alvarado [96], Chu et al. [97], Sainz de Murieta et al. [98], Dhyani et al. [99], Elum and Lawal [100], Esmaiel et al. [101], Espada et al. [102], Ferrari et al. [103], Khan et al. [104], Khan and Mishra [4], Lamond et al. [105], Lantada et al. [106], Lara and Moral [107], Leck et al. [108], Lindner et al. [109], Torres Mallma [110], McVittie et al. [111], Qi et al. [112], Rana et al. [113], Rivera et al. [114], Strang [115], Suditu [116], Tang and Lai [117], Thomas and Terry [14], Wamsler [118], Young [119], Zhong et al. [120]
	Mitigation measures	2	Baubion [121], Jain and Bazaz [122]
4	Community -centric	27	Ali and George [123], Buchori et al. [124], Canon-Barriga et al. [125], Castro et al. [126], Coates [127], Cui and Han [128], Fekete et al. [129], Guadagno [130], Gupta et al. [131], Kenney and Phibbs [132], Lara et al. [133], McEwen et al. [134], O'Grady et al. [135], Onyeagoziri et al. [136], Roder et al. [137], Rodríguez-Gaviria et al. [138], Ruszczyk et al. [139], Saad [140], Salami et al. [141], Miranda Sara et al. [142], Schaer [143], Shirleyana et al. [144], Smith et al. [145], Swapan et al. [146], Thouret et al. [147], Wamsler et al. [148], Ziervogel [149]
	Preparedness	5	Heinkel et al. [150], Holloway et al. [151], Silverman et al. [152], Yabe et al. [8], Yin et al. [153]
	Resilience framework and models	39	Adeyeye and Emmitt [154], Ajibade [155], Alberico et al. [156], Almoradie et al. [157], Alvarez and Cardenas [158], Anelli et al. [159], Attolico and Smaldone [160], Barría et al. [161], Bodoque et al. [162], Bozza et al. [163], Chelleri et al. [164], Cheng and Chang [165], Cremen et al. [166], Dianat et al. [167], Driessen et al. [168], Eltinay [169], Fauziyanti and Hizbaron [170], Feofilovs and Romagnoli [171], Feofilovs et al. [172], Frausto et al. [173], Gao et al. [174], González et al. [175], Hofmann [176], Huck et al. [177], Khazai et al. [178], Kumar S and C. A [179], Le Blanc [180], MacAskill and Guthrie [181], Matyas [182], Mukherjee et al. [183], Nozhati [184], Osman [185], Saravi et al. [186], Satour et al. [187], Sim et al. [188], Sou [189], Terblanche et al. [190], Velasco et al. [191], Webber et al. [192]

Sendai Framework and urban disaster risk management. Further, we give our perceived gaps and opportunities for implementing an urban digital twin as platform for disaster risk management towards urban resilience. Overall, the different studies reveal the multi-faceted characteristic of disaster risk, reemphasizing the need for continued research on individual and integrated topics, and on holistic management implementations. We illustrate these characteristics in Figure 8, highlighting the risk analysis process (as described in [28]) in relation to the phases of disaster risk management.

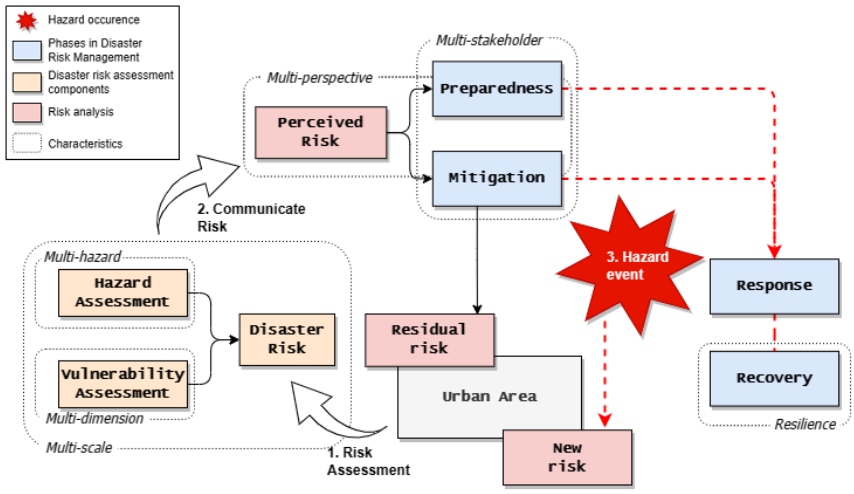


Figure 8: Multi-faceted characteristics of disaster risk and management.

5.1. Understanding urban disaster risk

5.1.1. Risk Assessment

Understanding disaster risk involves identification and understanding of all nuances of the components and dimensions that contribute to it: what the existing hazards and its impacts are; what elements at risk are considered and what their exposure and vulnerability to the hazard impacts are; what the coping or adaptive capacity of these elements at risk are—which are essential to effectively manage disaster risks [58, 66, 64, 72]. Due to its wide scope, it is common for projects and studies to focus on only one phase or component process of disaster risk management, but it is expected, and necessary, to integrate the outputs to the overall scope of disaster risk management—to identify how the results can be implemented to the connected processes, i.e. asking 'what are impacts?' or 'what are the consequences?'. Some of the identified challenges in disaster assessment methods

include: limitation of actual data and measurement; scale and/or resolution of the analysis; and type of statistical or spatial analysis applied [102, 106].

In urban areas, we also want to contextualize disaster risk by identifying the corresponding risk components and how the urban processes, such as urbanization play into the disaster risk and management [73, 183]. The need to understand risks in the different urban settings is now getting acknowledged [75, 76, 108, 141], since different communities experience disasters specific to their localities and the exposure of populations to hazards will not be homogeneous—usually with the urban poor, informal settlers, persons with disabilities and other marginalized population experiencing more negative impacts of the hazards [126, 176, 78, 136, 146, 69, 149]. The challenge of having unplanned, unmonitored or inappropriate urbanization is highlighted as having direct impact to increased vulnerabilities of cities and communities, particularly leading to informal settlements or unmanaged urban sprawl in areas of high risk [167, 100, 76, 63]. Alkinani et al. [73] even suggests that urban sprawl could be considered a disaster in itself which contribute to urban disaster risk as well. Thus, it is emphasized that disaster risk management is a necessary consideration in urban planning, such as incorporating hazard maps in improving urban development plans toward sustainability [30, 16, 102, 119], as prescribed in the guidelines for developmental programmes of governments.

It is evident from the different studies and projects that each risk component have their own complexities as well and the differences in these risk components across different communities and cities further add to the need of arriving at approaches that would be appropriate for each specific cases [30]. For example, in the case of vulnerability, it is defined by factors in several dimensions and is assessed with respect to the elements at risk considered to be exposed to the hazard in the area of study—identified based on the impacts of the hazard considered in order to define their specific vulnerabilities [58, 59, 61, 16, 65, 69]. This multi-dimensional nature of vulnerability assessment translates to different perspectives of risk assessment, that could look into physical, social, economic, and environmental aspects [61, 75]. People and urban processes are also continuously changing and exists at multi-scales in terms of spatial and temporal characteristics.

Hazards also vary across places, and modeling them oftentimes require their own dedicated research, commonly focusing on one or two specific hazard in an area. However, several studies [161, 60, 28, 16, 91, 110, 91] have emphasized the need for disaster risk management to be multi-hazard in order to understand how the hazards interact with each other. These multi-hazard assessments provide specific hazard indices [126] and holistic risk

assessment as important inputs for disaster risk management plans [161], which could be critical for emergent disasters or extreme weather events that a community may previously have not experienced, further emphasizing the influence of climate change in risk management and its linkages to urban planning and environmental management [102, 119]. This introduces additional challenges since different hazards would require different plans and strategies, but could be addressed through different models [58, 120].

5.1.2. Disaster data, integration and models

Risk assessment involves different aspects and the corresponding information and data are needed to perform the assessment process to derive the target indicators and outputs in multiple dimensions—including physical, social, environmental and economic—which can be from different sources [72]. The importance of data in all the processes of disaster risk management is stressed as a critical part of successful plans and outputs, as further evident in the studies of [59, 74, 121, 122, 67, 69], wherein they were derived comprehensive analysis from their historical disaster databases.

Common challenges are in data availability and accuracy, and the available software and models needed to be matched to the target outcome. Geospatial data and technologies are the most common data source and methods in disaster risk assessments, which may include satellite images, lidar, orthophotos and digital terrain models (DTM) and land use-land cover maps [70]. Ideally, there should be disaster database containing the the detailed information required to perform the necessary assessments, at different levels and scale of analysis [59, 138], including representative data needed to generate different number of indicators for the different risk dimensions [159, 63, 69]. Sometimes the disaster are in small localities and are not given priority due to challenges in data sources [125].

Sensor technology is already being recognized as real-time options for data availability [152] and data sharing platforms using new technology will be beneficial in improving data collection and utilization [106]. The increase in frequency and intensity of different hazards stresses further the importance of methods to understand, model and predict related process [115, 8]. Furthermore, understanding future risks and impacts would be crucial for sustainability targets [166].

5.2. Strengthening disaster risk governance to manage disaster risk

Urban disaster risk governance require multi-level, inclusive and multisectoral perspectives and engagement, as well as effective coordination between local and national government and relevant stakeholders (eg. govern-

ment sectors, private entities, local authorities, community) [97, 86, 88, 90, 116, 118]—to meet global commitments and targets, including the Sendai Framework. This is reflected in the UNDP strategic plan wherein they describe urban governance systems should have openness and participation, and is required to be "holistic and strongly risk-informed" [193].

5.2.1. Stakeholder coordination and collaborative risk governance

Residents who have a good understanding of their risk situation could be able to develop their own coping strategies, but may not have the means to change their situation in a meaningful way, as opposed to the authorities who have the means but not the information on local conditions to implement better precision and certainty in their actions [76]. Governments usually take a top-down approach in disaster risk management [124], but understanding the local situation helps to adapt city planning and policies, and develop targeted education campaigns and community engagement [119]. Studies have seen the need to bridge the gap between institutional and local perspectives [81], incorporating local knowledge and understanding with national disaster risk governance—a convergence of bottom-up with and top-down approaches [127, 131, 87, 128, 134, 135, 143, 145, 147]—which can be referred to as collaborative governance [83, 87].

In the studies, the coordination of stakeholders is realized as one of the important components necessary to make disaster risk management effective, especially towards urban resilience [154, 73, 66, 60, 28, 79]. One bottleneck that was seen is the fragmentation of agencies such that effective coordination do not work [84], calling for an integrated and coordinated approach in disaster risk management [154]. This includes establishing of roles and communication platforms [91] and clarifying hierarchies to push for more effective disaster risk management [81, 168]. This relates to the challenge of disaster risk communication—how to communicate the roles and responsibilities of stakeholders? What are the respective levels of participation? This devolution of responsibility to the local government and empowering communities to participate in the decisions is recommended and seen as a critical factor of successful disaster governance [89].

5.2.2. Community engagement and participation

In this shift to local and participatory governance, the community is expected to work together, but it may not always be the situation [127, 194] and in some cases this may be due to lack of trust with the government or wrong risk perception [137], or lack of awareness leading to to unwillingness to participate in disaster risk reduction process for some communities

[129]. Therefore, a participatory model of local disaster risk management should include empowerment [182, 134]. This is important since participation in disaster risk reduction activities improves perception of community resilience [128] and gives the community that sense of ownership, which lead to increased resilience of the community [135]. In a participatory disaster risk management, communities are encouraged to engage in all the phases of disaster management cycle on their own and in collaboration with the government [135]. Therein lies the challenge to encourage active participation of the community to collaborate in the disaster risk management process.

Participatory and inclusive approaches aimed at community-based strategies should be implemented to achieve the goal of sustainability [97, 82, 88, 105]. A shift from traditional expert-driven to community-driven disaster risk management process is suggested by Swapan et al. [146]. The citizens' participation in urban planning processes is valuable [194], though there maybe communities that do not engage actively, and there may also be instances when citizen engagement hinder the sustainability outcomes [148]. Effective leadership and communication between stakeholders is a key requirement to encourage the engagement and widen participation in disaster risk actions [160, 100, 105, 139]. Two issues are identified: shared understanding of the disaster risk context and management goals, and commitment of the stakeholders[87]. A disaster risk reduction framework should emphasize local participation and facilitate coordination [76].

5.3. Investing in disaster risk reduction for resilience

Due to the many factors that are at play, i.e. climate change, unforeseen extreme events and rapid urbanization, both short-term and long-term planning should be integrated in disaster risk management policies and strategies to be developed [157]. Disaster risk governance require long term planning and appropriate arrangements need to fit different contexts of government levels [168]. In some cases, the change of local government officials would require re-establishing the collaborative governance [131]. There should be continuity planning, anticipating risks setting mitigation and preparedness measures to increase and resilience and ensure continuity of public services and business [93, 121]. A big challenge that Torres Mallma [110] noted for some governments is looking at disaster risk management as an expense and not as a long-term investment for enabling solution.

In the urban context, besides relating to climate change adaptation and disaster management, urban resilience is now used to refer to the state leading towards the broader sustainability challenges, that is disaster risk management already incorporated in urban planning and decisions, e.g. devel-

opment of urban structure and services that can accommodate population increase while ensuring these developments are safe from expected and unexpected disasters [164]. This should ideally be embedded within institutional frameworks that enable disaster risk reduction and climate change adaptation within urban development [86, 105, 92, 192].

5.4. Enhancing disaster preparedness for effective response and to to 'Build Back Better' in recovery, rehabilitation and reconstruction

5.4.1. Risk perception and awareness

Local or community risk perceptions and awareness are mostly shaped by the residents' experiences [76, 133, 141]. Patri et al. [64] suggests this 'awareness' (eg. of climate change, policies, projects, etc) as an additional component in vulnerability assessment. In most cases, the community's perception of risks affects their level of preparedness to disaster risks, and different perceptions lead to different preparedness levels [105, 65, 153]. In some cases, residents are poorly informed about the risks in their locality or what their response strategies should be [4]. Thus, communicating risks is also one of the challenges in disaster risk management. Real-time alerts or early warning systems are necessary to inform the communities of impending hazards or emerging disasters, ideally with enough time in advance to give them the chance to respond to protect themselves [152]. Zhong et al. [120] believe that communication is the *core adaptive capacity* in community resilience—by providing the information on hazards and risks to the people. Promoting disaster risk education will influence the risk perception and helps the empowerment and adaptation of the community towards resilience, i.e. making development decisions and disaster recovery [128, 150].

Different understanding of risk and resilience exists within the different stakeholders [76, 127, 131, 87, 128, 134, 135, 64, 145, 147], and the different perceptions inspire different actors of disaster risk management into action as influenced by their priorities, scales, contexts, or interests[76]. There could also be instances where different stakeholders would have conflicting perceptions [107], thus a risk management approach should look at linking local risk perception and the authorities' knowledge for better understanding [157, 76, 190].

Holloway et al. [151] argue that developing the field of disaster risk reduction can be done in higher education to invest in skilled human capacity in this domain, which helps progress towards sustainability. Educational policies may be implemented to promote awareness and knowledge about risks and relevant knowledge [153], especially in the local and community level [142]. A practical example is the work of Gao et al. [174] where they

used "serious game" as an education tool for sustainability, at the same time a platform to analyze the players' decision-making process.

5.4.2. From disaster risk to resilience

Referring to the UNDRR definition of resilience (Table 1), achieving disaster resilience can be achieved through reducing risk components, mitigating disaster impacts or increasing the adaptive capacity of communities—thus resilience can be viewed of as the inverse of risk. Recent studies show this shift of focus from disaster risk to resilience [155, 157, 160, 162, 164, 170, 172, 62, 175, 179, 77, 189].

Studies agree that people are at the center of resilience, especially in integrating perspectives and stakeholder collaboration approaches and action [83, 100, 118]. Social resilience is critical to guarantee the success of management plans [162], which should be in parallel with communicating disaster risk knowledge and awareness—to translate to policies [98] and promote social responsiveness in all levels of society [100]. Feng et al. [62] refer to a 'resilience community' which represents the community's consciousness, technology and policy concepts regarding resilience.

Evaluating urban disaster resilience assists in better understanding climate change impacts [77], and as with disaster risk management, resilience needs to be assessed in holistic manner towards the necessary planning and policy-making to achieve sustainability goals. Governments are given the task of leading the innovation and developing the disaster risk management programmes [97, 104, 105]. It is difficult to assess the effectiveness of management strategies [180], or what measures should or could even be implemented in the first place [181], thus measures of urban disaster resilience have been introduced in several studies. Some of these are: Disaster Resilience Scorecard [73], community resilience index (CRIF) [123], Resilience Performance Scorecard (RPS) [178], Sendai Framework Local Urban Indicators Tool [188], and Risk and Resilience Monitor (RRM) [175]. These studies make use of different indicators to derive a resilience score.

Similarly, Osman [185] used 130 indicators in their resilience measure, while Satour et al. [187] utilized composite index with geographic information system approach to map resilience levels. Frausto et al. [173] looked into multi-scale and temporal measures of indicators in three dimensions: Resilience capacities, Consequences, and Learning and behaviors, implementing a principle of local participation. In the studies of Alberico et al. [156] and González et al. [175] they used the concept of disaster risk management and translated them to indicators for resilience. [191] implemented the Resilience to Cope with Climate Change in Urban Areas (RESCCUE)

project [4] to assess current and future resilience scenarios.

On the other hand, Feofilovs et al. [172] suggests that indicator-based approach may not capture the complexity of the system, which could be addressed with system dynamics modeling and instead used multi-criteria analysis and system dynamics model to create their Urban Resilience Index, which can be used for short term and long term resilience assessment. Dianat et al. [167] also extended indicator-based measures by using the Causal Loop Diagram (CLD) approach integrated with the UNISDR Scorecard as quantitative resilience measurement tool.

Prioritization also plays a role in implementing management strategies and policies, which can be done through an operable framework in place [165]. Huck et al. [177] further argue that prioritization should consider case-by-case circumstances, due to possible negative trade-offs. Ajibade [155] refer to a 'resilience fix' wherein false solutions are implemented that only transforms or shifts the disaster to other locations. Thus, in mainstreaming resilience-building, there is a need to understand resilience trade-offs [164]. Determining the city's 'resiliency' provides us a means to assess urban disaster risk management strategies [73] and understand risk profiles [169]. Bozza et al. [163] suggests that a measure of the resilience level leads to identifying best solutions after a disaster event.

6. Opportunities for urban digital twins in disaster risk management

There are still challenges in UDT implementation [26, 195], but have gained momentum in urban applications [56]; though the development are varied according to different urban management aims [196]. Yet, this emergent technology is seen to have great value, such as for planning, disaster prevention and improving accessibility for people [197].

We looked at the overall themes from the reviewed studies and present the research opportunities of implementing urban digital twins for disaster risk management to address its multi-faceted characteristics. We refer to descriptions from use cases and characteristics of urban digital twins implementation identified in recent and ongoing studies, and summarized in Table 7 with the related challenges they can possibly address. In a top level view, we see urban digital twins as enabling technology for urban disaster risk management activities in any or all of the following aspects: (i) As 3D

[4] `https://toolkit.resccue.eu/`

city database and visualization, (ii) As platform for collaboration and policy development, (iii) As model for simulating city processes, and (iv) As tool towards sustainable and resilient cities.

Table 7: Disaster risk management challenges as opportunities for urban digital twin implementation.

Theme	**Facet**	**Challenge**	**Urban digital twin use case/characteristic**
Risk assessment	multi-scale	Present local to national level of analysis	As 3D city database[2,5,6,7], multi-dimensional/ space-time/scale[4], integrating sensor network[2,3,6,7]
	multi-dimension	Incorporate different components of risk assessment (eg. vulnerability, hazard, exposure) from relevant dimensions including physical, social, economic, environmental	
	multi-hazard	Consider specific or integrated hazard data and models into disaster risk	
	multi-data source	Integrate different datasets from different sources, including real-time sensor data	
	future-scenario	Develop simulation and prediction models for different risk analysis	As platform for scenario modeling[1,2,3,4,5,6,7]
Stakeholder collaboration and participation	multi-perspective	Input perspectives of stakeholders from different sectors and facilitate unified understanding	As platform for participatory planning[1,3,6,7]
	multi-level	Set up of collaborative environment for different governance levels, eg. local, regional, national	
Risk perception	communicating risk (multi-perspective)	Present visualization of disaster risk and related elements for improved and unified understanding, and for risk information education	As 3D city model and visualization[1,2,3,4,5,6,7]
Resilience framework	resilience index	Provide dataset corresponding to specific resilience indicators and measurement	As 3D city database[2,5,6,7]
	resilience models	Analyze impacts of resilience and risk management strategies to the city through simulation models to discover prioritization or trade-offs	As platform for policy development[1] and decision making[7]

[1]Alva et al. [48], [2]Bauer et al. [52], [3]Dembski et al. [50], [4]Deren et al. [51], [5]Ferré-Bigorra et al. [49], [6]Ford and Wolf [34], [7]Lehtola et al. [27])

6.1. UDT as 3D city database and visualization

From recent and on-going urban studies, such as those mentioned in Section 2.3, it was demonstrated how digital technology can be utilized for modeling urban areas and necessary information for analysis. Research on

UDTs demonstrate its capabilities to support urban planning and management various spatial scales[26], and with a 'virtual city twin', the requirement of multi-scale disaster data and multi-dimension risk components of the urban area can be met [48, 51, 49, 34, 27]. In this context, the implementation of the UDT for disaster risk management would also further the research on addressing technical challenges including data management, integration and interoperability[26]. Seto et al. [195] noted the role of digitalization in constructing such 'digital cities' that integrate the big data that become widely available.

In the challenges of community risk perception and awareness, we see the UDT to serve not only as the data and simulation center for disaster risk, but set up the platform for risk information dissemination as well through 3D city visualization and user interface and interaction [48, 52, 50, 51, 49, 34, 27]. As real-time data—through sensor networks and spatial data inputs [52, 50, 34, 27]—and model outputs are continuously updated, the information that may be accessed by the authorities and communities are further improved, thus improving assessment, perception and awareness on disaster risks. In this aspect, UDT research can address opportunities for developing software tools that facilitate user interactions that allow insights in multiple perspectives.

6.2. UDT as platform for collaboration and policy development

Considering the different roles of stakeholders in urban disaster risk management and their different perspectives, a platform to unify disaster risk management efforts and be integrated and efficient is essential, to better incorporate sustainability initiatives as well. Alongside improved communication and understanding of the urban disaster risk through the UDT technology, it can likewise facilitate collaboration through participatory planning [48, 50, 34, 27]—converging top-down and bottom-up approaches in disaster management in a holistic perspective between national and local governments and the communities. Jeddoub et al. [198]—referring to these 'digital twin for cities'—consider that the technology can involve the various stakeholders and produce necessary information for improved urban decisions.

In the work of Alva et al. [48], policy development has been identified as the least explored use case for UDTs, suggesting opportunities for investigating UDT implementation that can integrate multiple perspectives and objectives of stakeholders in policy and decision making—in the case of urban disaster risk, in finding strategies across all phases of disaster management. In this regard, the benefits of UDT implementation to city should not outweigh consideration of the stakeholders who would be the intended

users of the technology [21], thus would require research on both technical and social aspects of the UDT i.e. capacity building [199].

6.3. UDT for simulating city processes

In the work of Ferré-Bigorra et al. [49], they refer to the 'simulation layer' in their generic UDT structure, which would be a module of the UDT that processes the city data for specific city services. Through application-specific models, the UDT is enabled to integrate urban data, software algorithms and artificial intelligence and use these in scenario modeling [48, 51, 49, 34, 27]—setting up research opportunities for these components, individually and integrated.

An important aspect of the UDT is as a framework for simulation models that can allow the generation of accurate predictions, informed forecasts and plans, and rational decisions, as described by Weil et al. [56]. Thus, with an UDT platform, processes relevant to disaster risk management, e.g. risk assessment—and its multi-dimensional components, i.e. hazards, vulnerability, coping capacity—could be undertaken, complemented with simulation and analysis of interdependent actions, such as in developing and testing mitigation models, assessing preparedness, formulating response strategies and simulating recovery action, as well as in anticipating emergent disasters and uncertain impacts of climate change as the city develops.

6.4. UDT towards sustainable and resilient cities

An underlying end goal of smart cities and urban digital twins is promoting sustainable development [50], and in consideration of disaster risks, towards resilience of the city as a whole [6]. A resilient city can be viewed to have the ability to respond to different risks [185]. There may be no one solution for reducing disaster risks [123, 89, 168], but we see the implementation of urban digital twins for disaster risk management as working towards addressing the challenges in an integrated perspective—towards holistic adaptation interventions and strategies, leading to action and sustainable change.

As urbanization continues and the city evolves, its models need regular updating which can be more efficiently managed through an UDT rather than traditional methods [49]. The challenge brought about by the complex nature of urban disasters and risks may not be solved all at once, but the UDT implementation can establish a framework and platform that could capture the disaster risk management cycle for continued analysis of short and long term solutions, through analysis of disaster data and scenario building within models—towards better understanding of resilience trade-offs and

prioritization of strategies. It is an iterative nature wherein the advantages of an UDT can be further explored [34].

6.5. Limitations of the study

In this paper, we aimed to conduct the systematic review in two stages, first to get a broad picture the urban disaster risk domain then progressively focusing in on disaster risk management, with emphasis on sustainability and resilience context. The search query chosen were intended to capture most of the relevant studies on the topic. Additionally, the review included literature search up to the end of 2022, thus, as it is usually the case with systematic reviews, we could expect a number of a few new papers on this topic published since then which have not been included. However, we believe we were able to capture the general trend of research as shown in Figure 2.

For the analysis of keyword co-occurrence, the selected keyword were based on personal topics of interest, and other relevant topics may have not been included. However, for the intended goals of the paper, the keywords select were enough, but additional keywords of interest may investigated in updated reviews and in proceeding with developing an urban digital twin for urban disaster risk management.

The implementation of the Sendai Framework is not easily assessed and in our review we only represent this through the review themes, which may not completely represent full or direct implementations of the framework. In the categorization of the journal articles into the review themes, the primary objective was to assess the distribution of the reviewed studies across the Sendai Framework priorities of action, however the categories are not definitive and in fact an article may have study scope covering more than one of the priorities. It should be noted though that the Sendai Framework priorities themselves are inter-related and the subject of disaster risk management itself not lacking in complexity, with different ways to interpret depending on the approach, perspective and domain—thus cannot be captured in simplified categories. However, the categories were used as guide for synthesis of he studies and simplify looking into the directions for furthering research.

Lastly, as the urban digital twins technology is still in development stage, and unified definitions and implementations still being studied, we only based our outlook of opportunities for UDT research from current and on-going studies. Our exploration of UDT implementation in disaster risk management is still on-going and not yet included in this review paper.

7. Conclusion

We performed a systematic review of published articles on urban disaster risk management, in the context of the Sendai Framework, since its introduction in 2015. In general, the volume of studies on the topic is increasing, and we view this development as indication of the continuous attention on the relevance of disaster risk management, and its many complexities cover different research directions. However, we could also view this trend as highlighting the on-going challenge in finding solutions to the related urban disaster concerns, i.e. continuous increase in disasters, in part due to climate change and changing urban landscapes. This requirement of constant updating and reevaluation of disaster risk management strategies can be effectively addressed by the urban digital twin, an evolving set of technologies and paradigms in urban management.

Keyword occurrence and keyword co-occurrence graphs were generated to get a general idea of the scope of the articles reviewed—with particular interest towards research on urban digital twins. It can be noted that there was no article from the screened papers where the keyword *digital twin* was mentioned, although there were 7 occurrences of the keyword *smart city*, an umbrella term that encompasses such nascent technologies and approaches. This finding further encourages our research directions in UDT development and implementation towards recognizing opportunities for technological solutions to the challenges of urban disaster risk management identified in Table 7.

Only 47 articles (33% of full-text review; 7% of total 659 articles profiled) explicitly or directly mention the Sendai Framework in their studies. This count may not capture the complete situation of the Sendai Framework implementation in scientific research—and indirectly other studies could have addressed the framework's targets as they implement disaster risk reduction research—however, this could also indicate the lack of intentional adoption or awareness of the framework despite being promoted as the guideline for global targets in disaster risk reduction.

Though not strictly definitive, from the categorization performed based on representative topics, relatively there were a good number of articles focusing on priority 1 (*Understanding disaster risk*), which is a positive indication that good bases for understanding of disaster risk and continuing studies on risk assessments are established, such that focus can now extend and connect to the other priorities of action. However, regular reevaluation of the risk assessments should still be available, especially as new situations emerge. It is with this in mind that we also think of the benefits of imple-

menting urban digital twins as possible technology to sustain disaster risk management, serving as data mdoel and simulation center to improve analysis and visualization for improved understanding of disasters and risks—leading to better disaster preparedness and developing of mitigation and recovery strategies, to meet priority 4 (*Enhancing disaster preparedness for effective response*).

Among the common themes from the review discussed in Section 5, the importance of risk awareness and perception is highlighted as a big factor that influences the actions and attitudes of the community to disaster risk, especially to engage their participation and collaboration in the disaster risk reduction and management. Education plays a strategic role for this, i.e. communicating risk to different levels of the society. It is the national government's task to communicate information about disaster risks and management process to the local governments who are then expected to coordinate with the community, setting up effective disaster risk management policies geared towards institutionalizing social and urban resilience, which would meet the aims of priority 2 (*Strengthening disaster governance*) and priority 3 (*Investing in disaster risk reduction for resilience*). This mutli-stakeholder perspective and multi-level collaboration objective for disaster risk management is another facet that can be facilitated with the development of the urban digital twin.

Further, it can be noted that at the core of the these themes is the importance of having people-centric disaster risk management, as reflected in the Sendai Framework and the other 2030 developmental agenda adopted by the UN. Overall, it was emphasized that disaster risk is everybody's business, and everyone needs to participate and be given a chance to collaborate in developing the strategies and policies towards effective disaster risk management. It is clear that there is no one-size-fits-all solution, and this multi-faceted characteristic of disaster risk calls for continued research to better understand and communicate risks to all concerned, improve risk perception and awareness of stakeholders, and integrate multi-level perspectives for inclusive governance and coordination among stakeholders—leading to opportunities for implementing urban digital twins to develop solutions to these challenges, especially towards a common goal of sustainable urban development and disaster resilience.

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Declaration of competing interest

The authors declare that there are no competing interests and do not have any conflict of interest they are aware of.

Data availability

No data was used for the research described in the article.

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