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Place-centred emerging technologies for disaster management: A scoping review

Matteo Baraldo *, Paola Di Giuseppantonio Di Franco

School of Philosophical, Historical, and Interdisciplinary Studies, University of Essex, United Kingdom

1. Introduction

Disasters increasingly threaten communities at a global scale, necessitating innovative approaches to risk reduction, response, recovery, preparedness, adaptation, and mitigation[1] [1]. Over the past few decades, the frequency and intensity of these events have escalated, highlighting the critical need for enhanced disaster management strategies. Between 2000 and 2019, over 7000 major disaster events were recorded globally, affecting more than four billion people, and causing approximately $2.97 trillion in economic losses [4]. Such statistics highlight the urgency of developing effective disaster management solutions. The Sendai Framework for Disaster Risk Reduction 2015–2030, developed by the United Nations Office for Disaster Risk Reduction (UNISDR), represents an important shift towards planning and investing for risk reduction to build community resilience.[2] The Framework advocates for such people-centred preventive approach to disaster risk management. This approach involves engaging with relevant stakeholders, such as civil society at large, and creating synergies across different groups, including academia and research institutions. This engagement allows for the appropriate and participatory design and implementation of policies, plans, and standards. Additionally, it contributes to raising awareness about a culture of prevention and education, and advocates for resilient communities within inclusive societies. Crucially, the Framework also emphasizes the importance of integrating advanced digital solutions and fostering inclusive community engagement to build resilience and mitigate the impacts of disasters [9].

Historically, disaster management practices have focused on reactive measures for post-disaster response and recovery, rather than proactive measures to prevent or reduce disaster risks. However, the advent of digital technologies is transforming the disaster management field, enabling more proactive and data-driven approaches. Technologies such as remote sensing, radars, satellite imaging, the Internet of Things (IoT), smartphones, and social media platforms are now integral to modern disaster management. These technologies facilitate real-time data collection and dissemination, enabling effective communication and coordination during disas-

* Corresponding author. School of Philosophical, Historical, and Interdisciplinary Studies, Office 6.148, Colchester Campus, United Kingdom.
E-mail address: matteo.baraldo@essex.ac.uk (M. Baraldo).

[1] Response, recovery, preparedness, adaptation, and mitigation are the main phases of what is traditionally known as the Hazard Management Cycle (HMC). This multi-phase cycle was first proposed by the United Nations Development Program (UNDP) and the former United Nations Disaster Relief Organisation [2]. As evident from Priority 4 of the Sendai Framework, which aims to enhance disaster preparedness for effective response and resilience building during recovery, rehabilitation, and reconstruction, the logic of the hazard management cycle (HMC) phases—though not in the foreground—still structures the core of the disaster risk reduction process and its policies. In this paper, we did not question the importance and effectiveness of the cycle, but we are well aware that many scholars have challenged it as an effective instrument for risk reduction and recovery [3].

[2] The complex etymology of resilience has been extensively studied [5]. In Latin, "resilire" means the act of rebounding. Since 100 BCE, it has been applied to various fields such as architecture (Vitruvius), natural sciences (Lucretius, Pliny the Elder), law and religion (Seneca the Elder, Seneca the Younger, Cicero, Quintilian), literature (Ovid, Petronius), and history (Livy, Florus, Marcellinus, Renatus). This term has been used to describe daily experiences in both tangible and metaphorical ways to represent the notion of rebounding [6]. To this day, the cross-disciplinary nature of the concept continues to influence studies in various fields, including engineering, ecology, anthropology, psychology, medicine, and social science. In social science, the concept has expanded to define social resilience as the ability of communities to withstand and absorb external shocks resulting from social, political, and environmental changes [7]. The International Federation of Red Cross and Red Crescent Societies (IFRC) focused on community resilience in its World Disaster Report of 2004 [8].

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ters. Consequently, they can monitor and predict disasters, provide real-time data for early warning systems, and assess damage in the aftermath of catastrophic events [10–12].

Recent studies, such as those conducted by Moez Krichen and colleagues [13] illustrate the transformative potential of these technologies. By focusing on their use in disaster management, these studies highlight how digital innovations can provide early warning data, enhance situational awareness, and support decision-making processes. Yet, despite these advancements, there remains a significant gap in our understanding of how other emerging technologies, like Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR) impact community preparedness and response to place loss and environmental trauma, which is what we intend to do in this paper.

These immersive technologies are selected for their unique capabilities to capture, analyze, and reveal the intricate relationship between humans and their environment. Unlike traditional digital tools, VR, AR, MR, and XR technologies can create immersive simulations that enhance situational awareness and preparedness. Their ability to visualize disaster scenarios can provide critical training for preparedness and support resilience studies. Furthermore, these technologies offer unique restorative capabilities by recreating lost or damaged places, helping communities to reconnect with their environments and fostering a sense of place and belonging, which is essential for psychological recovery. There is a need to explore the contribution of these technologies to the social dimensions of disaster management, which are often overlooked in broader technological reviews.

This paper aims to bridge this knowledge gap by reviewing the literature on the use of place-centric digital technologies in disaster settings. Understanding how these technologies address the social dimensions of human perception of risk and human responses to the loss of place during disasters is crucial for supporting long-term recovery efforts of communities and place.

This scoping review employs a place-centric approach to emphasize the intrinsic value of the human-place relationship, which is often overshadowed in human-centric frameworks that focus primarily on individual or community-level interactions. By centring on place, we highlight the unique geographical, cultural, and social characteristics that influence disaster preparedness and response. This approach allows to tailor technological interventions to the specific needs and conditions of each location, making disaster management strategies more effective and sustainable. In contrast, a human-centric approach, while valuable, might overlook the broader environmental context and the critical role of place in shaping community resilience and recovery.

Beyond their technical capabilities, these technologies could hold significant potential in addressing the social dimensions of disaster recovery, particularly in facilitating emotional and psychological healing and recovery of place-attachment. Irvin Altman and Setha Low [14] define place attachment as a complex phenomenon involving a positive cognitive and affective bond between individuals and their environment, shaped by emotions, knowledge, beliefs, and behaviours. Milligan [15] highlights that place attachment includes memories of past experiences and anticipated future experiences at a site. Disasters can disrupt these attachments, revealing the implicit meanings associated with a place. Milligan emphasizes that the significance of these meanings often becomes apparent only after the place is lost.

Unlike previous reviews that predominantly focus on the technical applications of these technologies, our scoping review aims to assess their contributions to the emotional and psychological recovery of affected communities. Understanding how these technologies address the social dimensions of human perception of risk and human responses to the loss of place during disasters is crucial for enhancing community resilience and supporting long-term recovery efforts [16]. Place loss refers to the emotional and psychological impact experienced by individuals and communities when they lose their place through disaster. Such loss produces sense of disorientation, grief, and identity disruption, threatening community cohesion and sense of self [17,18]. By recognizing the importance of place attachment and addressing the associated emotional and psychological impacts, recovery efforts can be tailored to not only rebuild physical structures but also to restore a sense of community and sense of place.

Previous reviews, such as the one by Khanal et al. [19], have focused on the application of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies in disaster management over the past years. This review categorized the applications of XR technologies into simulation modelling, interaction techniques, training, infrastructure assessment, and public awareness, providing valuable insights into the trends, opportunities, and challenges within this niche domain.

While these contributions are noteworthy, our review aims to provide a more comprehensive synthesis of the current state of research on place-centric digital technologies in disaster management. By identifying overarching trends and gaps, we aimed at evaluating the intersection of technology, place, and community, underscoring the importance of integrating technological innovations with strategies to enhance disaster resilience. This publication also highlights the need for constant updates in a rapidly growing field of research where changes occur very quickly. Considering that 77 % of the papers we reviewed were published after 2019, which is the final year for inclusion of papers in the 2022 review of Khanal et al. [19], staying current is essential. Based on these premises, the review process involved rigorous selection criteria, focusing on empirical studies that report on human experience and place-centric applications of digital technologies in disaster settings.

To structure our analysis, we focused on three pivotal research questions.

RQ.1. What are the most prevalent technologies used in place-centric research within disaster settings, and why are they favored?

RQ. 2. Which technologies are most associated with each phase of the Hazard Management Cycle (HMC)?

RQ.3. Are there examples where technology adoption in disaster management extends beyond technical deployment to emphasize community participation and integration?

Employing the scoping review method proposed by Arksey and O'Malley [20], we systematically mapped and synthesized existing literature to explore how digital technologies are applied in disaster contexts. Our aim is to provide a comprehensive understanding of the integration and impact of these technologies in enhancing disaster risk reduction and management (DRRM) processes. By prioritizing empirical studies, we aim to gather concrete evidence on how digital technologies facilitate human interactions, responses, and adaptations in disaster-affected areas. Emphasizing place-centric research allows us to examine the spatial context of these studies, which is vital for assessing the role of digital technologies in managing the human-environment nexus during disasters.

The reviewed literature was organized into thematic areas, including the types of disasters studied, the phases of the disaster management cycle addressed, and the specific digital technologies utilized. Our findings highlight significant trends and gaps in the current research landscape, providing a foundation for future investigations into the interplay between digital technologies and disaster management. The detailed analysis and synthesis presented in this paper aim to contribute to the ongoing discourse on integrating digital innovations to enhance the resilience and preparedness of communities facing disasters.

This paper aims to explore existing research but also to identify emergent trends and gaps, providing a critical evaluation of the intersection between technology, place, and community in the context of disaster management.

2. Methodological framework for literature review

Evidence on the use of digital technologies in disaster-related research was gathered following the scoping review method, a form of knowledge synthesis used to map and summarize a body of literature on a topic area [20]. In line with the study research questions, we have devised a query and use it to search the academic database Web of Science, using both full words and abbreviation. The query aims at capturing any sort of described digital technologies in its relevance and connection with disaster (or synonyms) related to place-centric research (see Table 1). Furthermore, this literature search terms aligns with the scoping methodology, an iterative process suitable to investigate the heterogeneity of multidisciplinary research methods, designs, and topics [21].

The year 2014 was selected as a significant milestone, marking the onset of increased investment by major big data companies in VR-HMD technology and the concurrent development of the metaverse. Furthermore, given the rapid pace of technological advancements, a ten-year span was deemed appropriate to capture the most pertinent trends.

At the selection stage of the study, we proceed to define inclusion and exclusion criteria. One of the main foci was to evaluate the presence of any digital technologies applied to disaster context where humans or communities have a precise role in the definition, test or evaluation of such technologies. The following inclusion criteria were applied.

- o application of digital technologies to disaster setting;
- o reporting on the human experience of digital spaces, including participation into experiments;

Publications were excluded if they do not report on the findings of an empirical study with a strong emphasis on a human- and place-centric approach, such for instance literature reviews, conceptual studies or studies aiming at reducing the human intervention in favour of robotisation. Accordingly, the following exclusion criteria were devised.

- o absence of empirical or practical application and test;
- o paper presenting reviews;
- o papers dealing only with theoretical considerations;
- o papers focusing only on technological aspects.

Examples of excluded publications include articles dealing solely with digital technologies applied to buildings and infrastructure protection and rehabilitation; modelling and visualization for predicting disasters; use of 3D printing or digital educational tools in disaster or emergency settings without reference to place or space; paper exclusively addressing prototyping, visualization, or similar technical aspects related to disaster management.

Based on the inclusion and exclusion criteria, reading titles and abstracts, the final sample was defined (n = 85). The overall search process is detailed in Fig. 1.

Following the methodology described by Arksey and O'Malley [20], we have charted the data deciding which categories information we aimed at extracting from the papers. Reviewed papers were then organised with their bibliometric indicators (year, country, journal) and collated in a table divided by research domain, disaster type, phase of disaster, type of technology and findings about its role in DRRM process, human-environment nexus, participants' role in the research process, type of space/place considered in the publications, and limitations.

First, attention was given to basic numerical analysis of the nature of the studies included in the review. This supported the analysis of the distribution of studies across diverse research domains. Using an inductive method supported by a descriptive-analytic model [20], the researchers identified the research domains. We attempted to use the Web of Science visual analytical tools, but they

Table 1
Scoping review query.

Topic 1 search	Topic 2 search	Topic 3 search
(({Digital} OR {Technologies} OR {XR (Extended Reality)} OR {AR (Augmented Reality)} OR {VR (Virtual Reality)} OR {MR (Mixed Reality)} OR {360-degree} OR {3D technologies}) AND	({Disaster} OR {Calamities} OR {Catastrophe}) AND	({Space} OR {Place} OR {Environment} OR {Community} OR {User} OR {Citizen}))

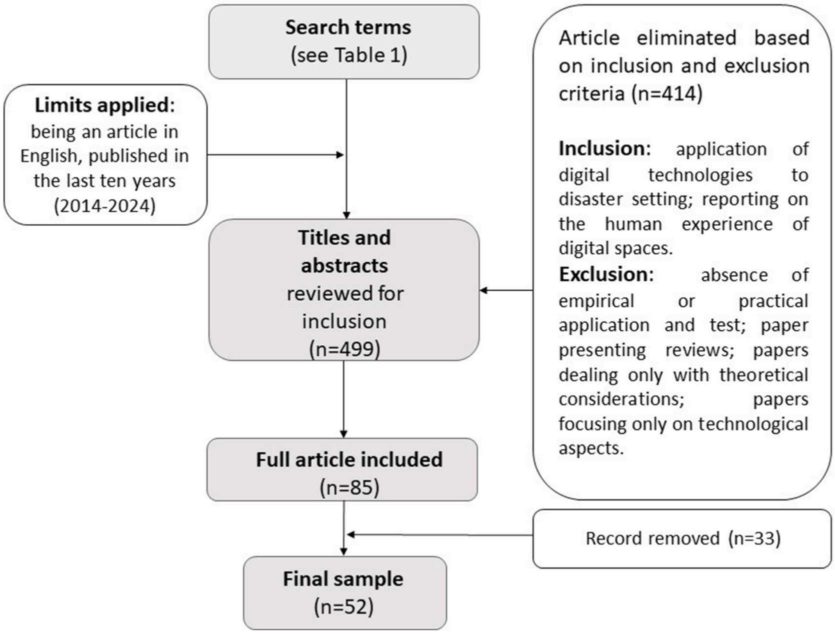

Fig. 1. Literature search process.

resulted in very broad and generic results: the label 'multidisciplinary' was automatically added to four categories grouping 22 papers (42 %). Therefore, categories were inductively deduced to achieve a more refined regrouping. The authors elaborated definitions to explain the label chosen for the research domains, aiming to express the main characteristics of each category identified through the inductive reasoning on extracted data (see Table 2). The list of initially identified research domains was iteratively expanded and cross-checked during the extraction process, particularly during the full-text reading stage. As a result, five main domains were discussed among the authors and selected as final categories.

Subsequently, the authors considered the positioning of the study within the Hazard Management Cycle and if it relates to a specific disaster (or else was tributed to a category named 'multi-hazard') and the range of technologies included in the review. The system allows a rapid appraisal of main technologies and main sector of interventions. In addition, the screened data are displayed to show whether digital technologies are supporting any phase of the DRRM standard activities not only 'technically', but also socially. In relation to the social implications, the role of participants in the research process was examined to understand the type and level of involvement of those who participated in the study. As place and space are framed as vital foci of the research, the type of spaces taken into considerations by each publication is presented as a stand-alone category, presenting differences such as indoor/outdoor, public/private, large/small extension, etc. that could add details to the fine-grain analysis of the role of digital technologies in the relationship between humans and space in time of calamities. Finally, the limitations presented in the papers are outlined to provide a more balanced perspective, highlighting the main areas of concern. Consequently, the identification of significant gaps and trends are made evident by the overview of the data presented.

All papers included in the final scoping review selection were reviewed by both authors. In the event of disagreement on inclusion within the sample, the authors re-examined the item and jointly decided. After the screening of the entire texts and further elimination of records (n = 33), mostly as they did not align with human-centric aspects or present any feature of space/place, the complete scoping review process produced a total of 52 publications for review and discussion.

Table 2
Definition of research domains and reference to relevant section.

Research domain	Definition of category	Section	Publications
Computer Science	Group publications primary linked to Software Engineering, Human-Computer Interaction, Database Systems, Computer Graphics, Information Technology	3.1.1	[23–52,68]
Health	Includes publications dealing with physical and psychological well-being	3.1.2	[53–60]
Media	Group publications on journalism, social media, and communication	3.1.3	[61–67]
Spatial Planning	Group publications focused on improving visualization and participation in planning and designing internal and external spaces related to disasters (from prevention parks to shelters)	3.1.4	[69–72]
Heritage	Includes publications on archaeology and heritage-related studies	3.1.5	[75,76]

3. Results

3.1. Research domains

Fig. 2 illustrates the number of reviewed publications by year over the past decade (2014–2023). Since 2022, our results suggest that there has been a consistent rise in interest and utilization of Extended Reality (XR) technologies and digital technologies applied to disaster management cycle across various disciplines and research domains.

Fifty percent of researchers contributing to the reviewed publications are affiliated with Asian universities (including East, West and South Asia), aligning coherently with the higher prevalence of disasters on the Asian continent (Fig. 3). This region has accounted for the highest mortality incidence since 2003, with an increasing trend noted in 2023, reaching 73.4 % of the overall worldwide disaster-associated deaths [22]. In terms of specific countries of affiliation, China and the United States are the most frequent, with 15 and 9 reviewed papers, respectively.

The papers selected for review were found in 44 journals, with an average of one contribution per journal and a maximum of three. This reflects the cross-disciplinary mapping of the intersection of three topics studied by a broad range of disciplines. After browsing each journal's aims, scope, and overview, the publications were assigned to a main journal domain (Fig. 4)

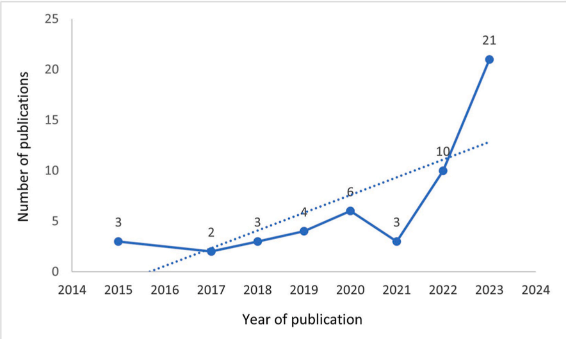

Fig. 2. Publications per year (last ten years).

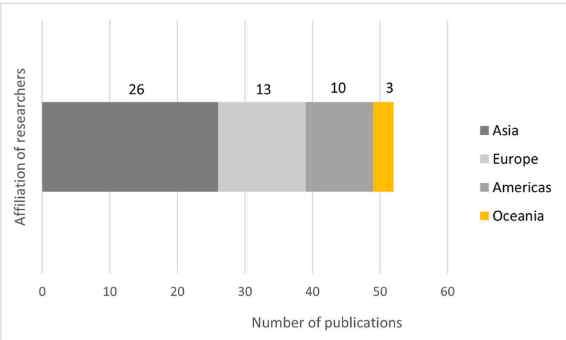

Fig. 3. Affiliation of researchers per regional cluster.

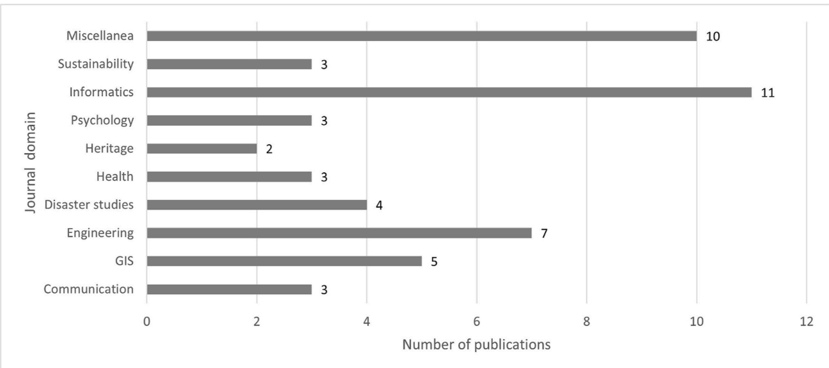

Fig. 4. Distribution across various journals (categorized by assigned domain).

After screening the contents, the reviewed publications were categorized into five primary thematic areas (Fig. 5), as per the methodological framework described above in Section 2.

The main refinement, compared to the categorization by journal domains, was the definition of a common denominator: many cross-disciplinary publications encompass information processing, elements of computer science, and the application of information technology as core features. The authors decided to classify these diverse papers under 'Computer Science', supported by the fact that Topic 1 of our query revolves around digital technological aspects.

3.1.1. Computer science

'Computer science' includes a significant portion of publications (comprising 23 % of the total reviewed papers) utilizing VR to digitally enhance readiness and preparedness for emergencies caused by disasters. Specifically, these publications focused on enhancing the evacuation process and disaster related training systems. It was observed that enhanced evacuation simulations and drills proved to be more effective than traditional non-digital methods [23–34]. One core argument presented was the utility of VR in increasing disaster knowledge and education. Additionally, 11 % of the total screened publications utilized VR and simulation to enhance decision-making skills as part of the preparedness cycle [35–40]. A relatively limited number of studies (6 %) applied simulation to enhance risk perception and overall understanding of hazards [41–43]. A similar number of publications (8 % of the total reviewed) explored the use of MR technologies to enhance the performance of indoor and outdoor rescue operations, with immersive teleoperation of rescue robots proving superior to traditional methods [44–47].

Further exploring the computer science and technology nexus, Li et al. [48] described an assisted escape system aimed at enhancing evacuation drills. Their study involved sensing virtual accidents through human/environment/computer-assisted interaction using MR. Similarly, Yoo and Choi [49] assessed an AR-based emergency evacuation navigation system tailored for indoor disaster environments, leveraging IoT and machine learning technologies. By harnessing the capabilities of digital mapping, Tillekaratne et al. [50] investigated the potential for enhancing the incident-reporting process using visualization software, facilitating timely outputs sharing among stakeholders. Schröter et al. [51] proposed value-added mapping for crisis management. Applicable to both response and preparedness/mitigation phases, Crawford et al. [52] suggested a web-based Internet clearinghouse utilizing GIS for post-disaster reconnaissance surveys, coupled with 360-video and deep learning to aid in data storage, dissemination, and analysis of community and extreme event data. Vera-Ortega et al. [53] designed a wearable sensor suite for real-time monitoring and recording of biosignals, intended to support search and rescue missions while considering the importance of wellbeing.

3.1.2. Health (including psychology)

Within the health thematic area, some publications [54–56] focused on developing and testing training programs for mass casualty response, demonstrating an enhanced educational experience. One key advantage is that digital technologies such as VR can provide unique opportunities for practicing skills in settings that students are unlikely to encounter during their standard medical internships. Notably, Lowe et al. [56] found in their cross-sectional observational study that among 207 participants (including residents, attending physicians, and non-physicians), a 360-degree VR setup represents an optimal and technologically accessible platform for experiences aimed at assessing preparedness for disasters. Other publications notably addressed psychological aspects. For example, Gamberini et al. [57] described the results from a series of sessions of co-design for a VR simulation aimed at increasing safety perception and risk awareness among people living near rivers, thus potentially impacting the well-being of those constantly exposed to the risk of recurring disasters. Additionally, some publications focused on stress control in emergency management [58] by integrating VR technology with the capture of physiological data, simulating earthquakes to measure and regulate anxiety [59], and comparing the delay time and speed preference between VR evacuation and real-world evacuation scenarios after a fire in a dormitory [60], highlighting the role of awareness and intensity of stimulation in the interaction between humans and their environment. Finally, leveraging the power of social media, Jiang et al. [61] studied risk response by conducting sentiment analysis on media posts from a sample of over 10,000 posts. The research focus on the performance of Online Collaborative Document (OCD) during the 2021 Henan flood. The OCD served as a distinctive space for experiencing affective dimension of the disaster, conveying the collective and public

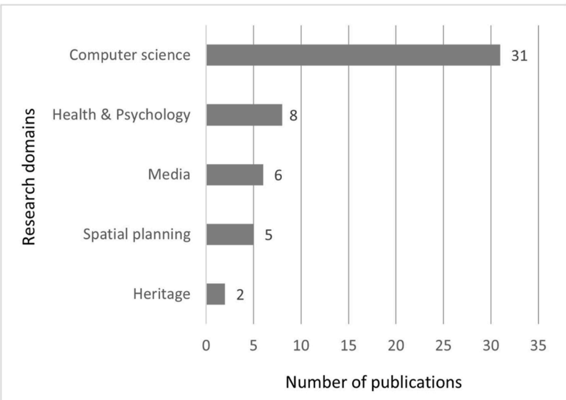

Fig. 5. Number of publications per research domain.

feelings of disaster victims, volunteers, government officials, and other netizens. Communication within this digital affective space not only centred around emotions but also facilitated social interactions.

3.1.3. Media

Among the reviewed publications, those categorized under the media domain underscored the relevance of traditional non-immersive digital media within the response and recovery phases. Casey et al. [62] discussed the use of social media to support creative adaptation to climate change. Wynn [63] elaborated on the role of place-based online communities during times of crisis. One of the main takeaways is that the potential for action lies at the intersection of online and offline connections. User-generated content can significantly impact traditional media, social interactions, and community, serving as either a benefit or a harm as well as having specific accessibility issues.

Madianou [64] found that social media enabled communities to build resilience through media environment, in particular existing social networks, enabling the community to seize opportunities to bounce back better after the disaster, such as finding a job or raising funds for charity works. Burns [65] examined volunteered geographic information (VGI), such as crowdsourcing and mapping tools like Ushahidi or Humanitarian Street Map and concluded that the generated knowledge from ground digital humanitarian data supported the response phase by potentially capturing emotional and social networks related to urban infrastructure. In fact, the community-based approach frames the types of data produced and the ways in which that data is represented in disaster contexts. Regarding the use of immersive media in journalism, two publications explored 360-degree media, yielding controversial results. Van Damme et al. [66] argued that a higher level of system immersion in news leads to a greater sense of presence in international disaster news but questioned the role of 360-degree videos as an 'empathy machine'. Conversely, Fraustino et al. [67] suggested that such media could enhance positive attitudes toward disaster content.

3.1.4. Spatial planning

Spatial planning is linked to both the preparedness and recovery phases of disaster management. Technologies are used for multi-hazard training in urban open-space scenarios, exemplified by De Fino et al. [68], who prototyped a Virtual Reality Serious Game (VR-SG). This experience in a virtual environment addresses both slow-onset disasters (such as heat waves) and sudden-onset disasters (such as earthquakes), integrating external simulations of outdoor temperature, falling debris, and crowd motion under representative typologies of the built environment. Zhu et al. [69] explore leveraging the power of GIS and Virtual Geographic Environment (VGE) to improve disaster scene visualization. Their empirical study analyses heat maps from eye movement experiments using three sets of experimental materials: animation, pictures, and written reports. The visualization varied based on user type (general public, affected people, rescuers) and device (laptop, interactive meeting board, mobile phone, mobile VR headset), using the insight from the participants to design a suitable visualization framework.

A common thread among publications dealing with spatial planning in the recovery phase is the emphasis on participation, as illustrated in the case study of designing a Disaster Prevention Park by Zhang et al. [70]. Here the authors describe a cloud-based VR platform enables proposing design concepts and discussing design alternatives during a design review meeting conducted over the Internet.

Another instance of the centrality of the participation is represented by the proprietary web-based GIS tool, used in their research by Giampieri et al. [71]. The scholars conducted workshops aimed at eliciting a vision, utilizing a platform where lifestyle and climate parameters could be selected and environmental performance set, resulting in a GIS-powered map where data are visualized based on selected preferences. Such digital maps could serve as prompts for discussion during workshops and aid in envisioning participatory spatial planning more effectively. Notably, Li et al. [72], by delving into the emotional and phenomenological nuances of recovery, transversally linked to the theme of public/private space design and wellbeing, monitored digitally acquired biosignals (such as EEG and LEC) to study the influence of post-disaster emergency building design on emotional recovery. The authors particularly focused on temporary emergency shelters, simulating them in a semi-circular dome-shaped test chamber with a 2.4 m radius as the controlled physical environment for the experiment.

3.1.5. Heritage

Within disaster heritage studies, the use of digital technologies often revolves around the technical reconstruction of artifacts and architectural elements of various scales. This serves both to preserve the memory of lost landscapes, as exemplified by Giannone and Verdiani [73] in their examination of the city of Messina, and to perform instant preliminary structural assessments through methods such as photogrammetry, aimed at preventing further collapses, as demonstrated by Kallas and Napolitano [74]. However, although initially identified through database queries, both publications were excluded from the reviewed papers upon full-text examination, as they do not address social aspects or community involvement in any form. Taking a different approach, Süvari et al. [75] presented an AR-based virtual restoration of tangible cultural heritage as a means to allow the experiencing of architectural elements of a church lost after a disaster. The impact was limited to contributing to individual visitors' stronger perception to the cultural assets via AR solutions. Similarly, Matini et al. [76] proposed, alongside technical aspects for the reconstruction of an adobe citadel, the use of AR to provide an augmented on-site experience and VR content to enhance accessibility, allowing visitors to have a remote digital experience of the reconstructed spaces. Although some of the research outputs are available online (http://drr.nii.ac.jp/Bam3DCG/), the virtual experiences were mainly linked to a limited number of demonstrations.

3.2. Type of disaster and HMC phase

Considering the types of disasters they address, 23 % of the overall publications were categorized as multi-hazard, indicating that the studies targeted aspects not specific to a particular type of disaster (Fig. 6).

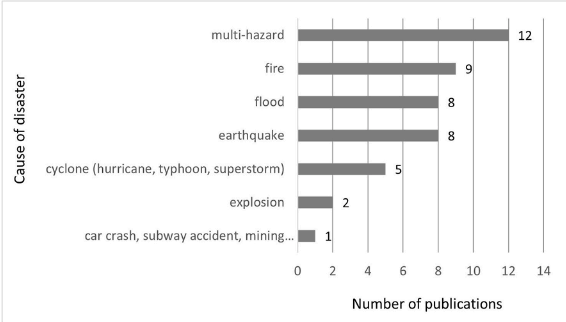

Fig. 6. Main causes of disasters within the reviewed publications.

Among the specific disaster types, fire (17 %), flood (15 %), and earthquake (15 %) were the most studied, followed by cyclones (10 %). Natural hazards collectively account for triggering disasters in 58 % of the reviewed publications. Conversely, only a few studies focus on more specific types of disasters that are not triggered by natural hazards, such as explosions, car crashes, subway accidents, mining accidents, dam disasters, mass shootings, and crowd disasters. These account for 17 % of the overall screened papers.

Each publication was screened and assigned to a phase of the Hazard Management Cycle The majority (71 %) of publications pertain to the preparedness phase (Fig. 7). Although publications related to the response phase cover a wide range of themes, it is noteworthy that two third of the papers in this category focus on psychological aspects of response to disasters. Regarding the recovery phase, spatial planning and heritage are the predominant themes covered.

3.3. Technologies

More than half (56 %) of the digital technologies utilized in the publications were VR or a combination of multiple technologies where VR was the predominant one (Fig. 8).

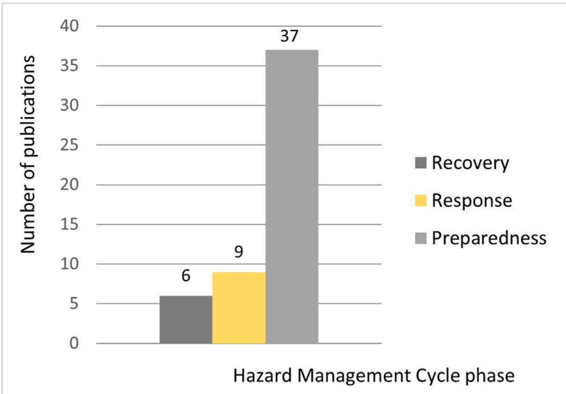

Fig. 7. Publications grouped according to phases of Hazard Management Cycle.

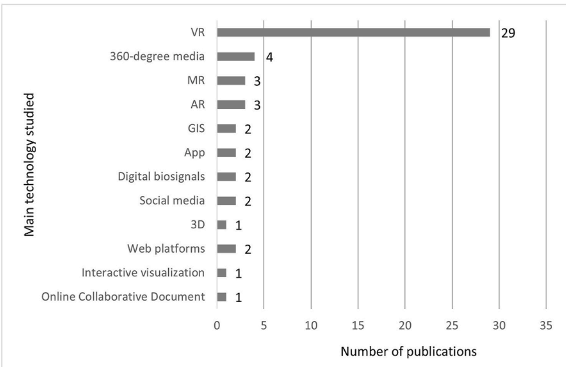

Fig. 8. Digital technologies applied to DRRM.

VR was used as a standalone technology or in combination with other digital solutions. For example, Dang et al. [24] associated it with Lidar scanner and 3D modelling; Xu et al. [28] utilized iwDome for immersive visualization, while in most cases, standard HMDs were employed; Kamezaki et al. [47] combined Gazebo, a collection of open-source software libraries for development of high-performance applications with Robot Operated System (ROS) joystick and pedals to operate a multi-limb robot named Octopus. On certain occasions, physiological signals were recorded under laboratory environment control (LEC) conditions allowing increasing or decreasing of the temperature, such as electroencephalography (EEG) [72], electrodermal activity (EDA) and electrocardiogram (ECG) [39], and blood pressure (BP) and hearth rate (HR) [58]. Often, VR experiences were enhanced by spatial sound and/or sound effects, as seen in the works of Kman et al. [55], Gamberini et al. [57], Lowe et al. [56], and Kamezaki et al. [47]. More than half of the publications (n = 15) focused on the use of VR declared the use of the Unity game engine to facilitate effectiveness in interactions with the virtual environment, focusing on immersivity and a more apt user-centred interaction with the virtual environment. Considering only the main technologies with a representation above 5 % (n = 4), all fall within the XR spectrum, including MR, AR, and 360-degree technologies. All these technologies were applied to the preparedness phase, with the majority being represented by VR solutions (Fig. 9).

Among the reviewed papers, VR was largely used as support to preparedness. VR and AR were predominantly utilized for research focusing on the recovery phase. MR and VR were primarily utilized for studies concerning the response phase. 360-degree technology was exclusively used for studies related to preparedness.

3.4. Role and impact of technologies in the Disaster

Publications focusing on training represent 52 % of the overall reviewed papers (Fig. 10).

The development of capacities for digitally supported emergency preparedness is paramount. Evacuation simulations are prevalent among the reviewed publications [23–25,33,40,42,49,68]. A significant subset of publications deals with digitally enhanced emergency and safety drills, encompassing MR-assisted escape systems [48] and indoor disaster rescue [45], VR-based simulations of disasters [28,31,32,34,59] or AR-based fireground situation training [30]. Several opportunities for virtual practical education experiences are presented, related to the training of healthcare professionals [54,56], firefighters [35], and emergency personnel [55]. Some of the training aims to create knowledge of disasters and build preparedness in general [43] or guide the design for creating VR environments with disaster scenarios for educational purposes [29,33]. There is also a specific subset of publications dealing with capacity building in robotics-related rescue operations, such as controlling exploration robots [46,47].

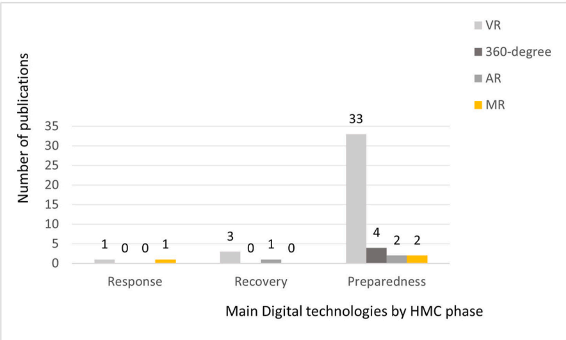

Fig. 9. Main Digital technologies by HMC phase.

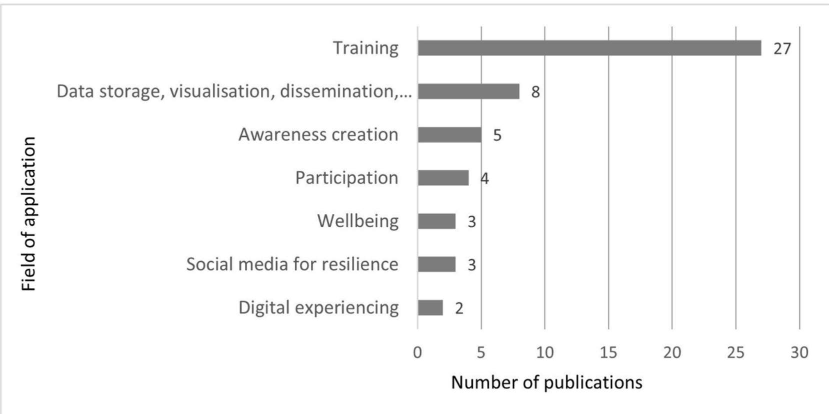

Fig. 10. Role of digital technologies in DRRM.

'Data storage, visualization, dissemination, and analysis' represents the second most frequent category (15 %). A series of publications work toward enhanced visualization, monitoring, and reporting of data to make them accessible, shareable, and reportable. For instance, Tillekaratne et al. [50] compiled human-related data into a georeferenced visualization to produce and share a situation report, a standard tool often used in emergencies. Sermet et al. [37] presented a framework for generating real-time 3D models, dynamically adding interactive information that can be shared among multiple stakeholders to enable collaborative decision-making about the intervention in the disaster. Similarly, Lin et al. [27] discussed an intelligent disaster prevention system for data collection and analysis displayed through a 3D visual model which provide a more accurate description of the disaster location and support both disaster preparedness and relief. Prevention is also at the core of the study by Zhao et al. [39], who tested several crowd management strategies to enable preventive strategic decision-making. With a slightly different focus, Deng et al. [60] established a framework for data comparison between VR evacuations and real cases of evacuation after a fire in a dormitory, akin to perspectives expressed by the process of built environment investigations conducted by architectural forensics. Data were also central for value-added mapping for crisis management [51] and to test a web-based Internet GIS platform for post-disaster reconnaissance survey able to meet the needs of the research community as well as communities located in vulnerable areas, in terms of facilitating the extraction and classification of large volumes of visual data from passively collected, vehicle-mounted 360° video [52].

Most of the studies within the category 'awareness creation' (10 %) leverage virtual environments and simulations for a more attuned risk perception. Zhu et al. [69] tested a disaster scene virtual visualization through an eye-tracker-based cognitive experiment on disaster scenes. Others envisage the effects of disasters on simulated residential homes and surrounding areas [41]. Similarly, Gamberini et al. [54] described an interactive virtual experience that can increase safety perception and risk awareness in people living in proximity to a river.

Concerning participation (8 %), Jiang et al. [61] debated participatory, dynamic, and constructive risk communication and information-sharing networks related to the Zhengzhou flooding event. Giampieri et al. [71] supported the mobilization of the community in a disaster-prone area (Jamaica Bay, NY) through resilience planning. An internet-based modelling software is employed to create 'visions of resilience,' i.e., future land management and planning envisaged by local communities. Burns [65] advocates for 'digital labour' and activism for disaster response; Zhang et al. [70] support the improvement of consensus with real-time design experiments.

'Wellbeing' (6 %) is a limited category found in our study (n = 3). However, all phases of disasters are covered, considering the measurement of physiological signals of stress control during a safe evacuation of personnel [58], a human-robot joint search and rescue mission [53], and a post-disaster temporarily displaced population [72].

Social media (6 %) was studied as supportive of resilience by Casey et al. [62] in the case of a slow onset disaster (drought) as a form of marketing, as a platform for the dissemination of online community-generated maps [63], or as a media environment in which social networks could be maintained in times of crisis [64]. Lastly, heritage (4 %) goes beyond the mere reconstitution of lost environments in post-disaster settings, leveraging 3D and XR technologies for different forms of re-experiencing [75,76].

More than half of the reviewed papers investigated the impact on behaviour during emergencies or the acquisition of knowledge on safety measures across various disasters and contexts (Fig. 11).

Fifteen percent of the publications directly addressed the impact of digital technologies on communities, with studies/cases/research encompassing the use of technologies for information sharing [61,63], communication processes [66,67], socio-economic resilience [62], involvement [70,71], and activism [65]. Another 13 % of publications focused on aspects of disaster management through VR-enabled simulations (37–39,51,58]. Other publications discussed the importance of accessibility [75,76], particularly concerning heritage affected by disasters; the necessity for tailored risk perception [41]; and disaster awareness and preparedness [29,43]. Lastly, emotional recovery and embodied dimensions of post-disaster recovery were considered by Li et al. [27].

3.5. Participants

In terms of participants, the majority of individuals involved in the diverse experimental settings were generically categorized as 'users' (46 %). These users primarily contributed to exploring the interplay between humans, digital technology, and the environment. They comprised a group of research participants, usually fewer than 50, where researchers deemed additional distinctions, such as socio-demographic characteristics, unnecessary beyond their role in testing and utilizing deployed digital solutions (Fig. 12).

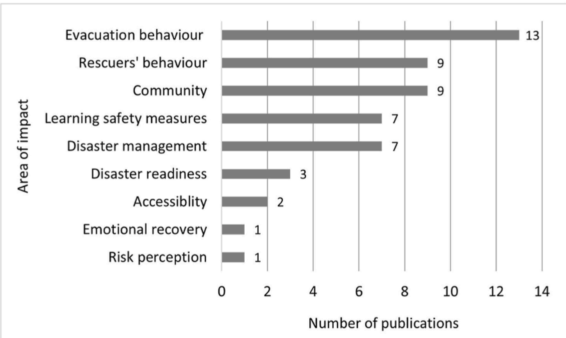

Fig. 11. Studied impact.

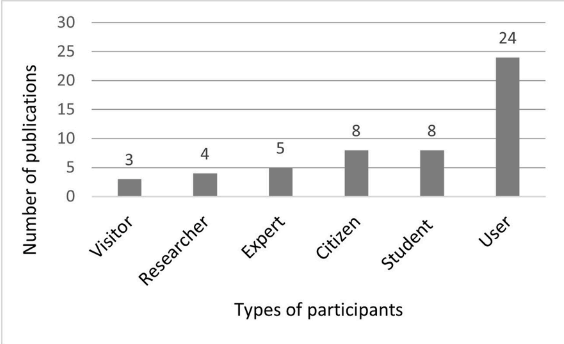

Fig. 12. Participants.

Fifteen percent of the publications specifically targeted students, with experiments conducted over relatively large groups of participants (over 100) [28,30,56]. Although most of the involved participants were certainly also citizens, the category was chosen to indicate attention within the studies to the presence of a group and/or community where a shared public opinion could emerge, as in the case of the COPs (Communities of Practice) identified by Giampieri et al. [71], rather than focusing on individual attitudes. Mixed methods such as participant observation [64,65] highlight the focus on qualitative analysis and interest in larger societal dynamics.

Another subset of participants is represented by what we have termed 'experts' (10 %). Professional rescuers such as firefighters [35,53] or emergency operators [44,46] tested the efficacy of the devised systems. In one instance [57], involvement in disaster management was indirect, as experts participated as co-designers of immersive and interactive virtual experiences. In some cases, researchers were directly involved as the main focus was to devise solutions to meet the needs of research communities studying disasters, as seen in the work of Crawford et al. [52]. Lastly, visitors were targeted in a few studies (n = 3), particularly in the heritage field [75,76].

3.6. Types of spaces/places

In this subsection, we will focus on the data we have extracted regarding the configuration of spaces and places. As depicted in Fig. 13, the largest captured category was the territory, which is understood as a map-type representation of large areas existing in the real world.

Among these spaces, territories covered include four American states [37], Dauphin Island, Alabama [52], Jamaica Bay [71], Rockaway peninsula, New York [65], Northampton, Massachusetts [63], Queensland, Australia [62], Banmen town, Sichuan Province [38], Niaodao Island, China [33], The Hague, The Netherlands [51], the adobe citadel of Bam, Iran [76], and locations in the Philippines archipelago such as Tacloban, Leyte, and Sabay, Cebu [64].

Additionally, the analysed papers investigate various buildings and built environments. Schools were an important setting studied [28,31,45,59]. The buildings examined range from residential structures [41] to large multi-floor constructions [40], just to mention a few. Outdoor urban space was also a focus, including cityscapes, train stations [24,27], and areas designed for large gatherings, such as the Duisburg festival area covering 100,000 m2 [39].

In relation to the urban environment, the depicted spaces were either hypothetical urban areas modelled on typological geometric features of urban open-spaces [42,68] or limited real sections of an urban landscape [35]. Outdoor natural spaces were also studied, including riverine areas [57,61] and disaster-stricken and/or prone valleys [36,43,69]. The term ‘disaster space’ refers to settings designed for emergency scenarios, including staged emergency care post-disaster sites [56], simulated environments for debris entrapment rescue [46], 3D modelled temporary emergency shelters [72], and indoor and outdoor experimental zones where disaster conditions such as rubble were recreated for safety training purposes [44,53].

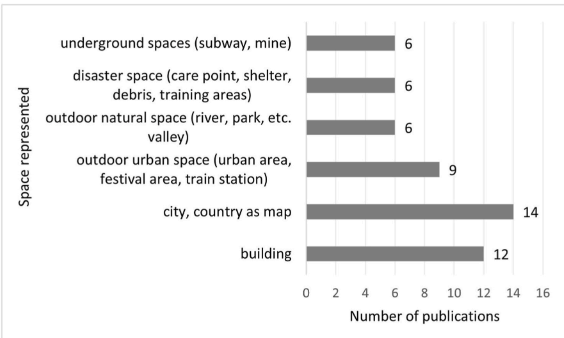

Fig. 13. Types of spaces/places.

Lastly, concerning what we have defined as 'underground space', studies include tunnels [54], mines [32,48], and especially subways [55,58]. Spaces are both limited in extension and modularity, from a ground floor of a building with an area of approximately 330 m2 to a subway train station with carriages, measuring 100*100 m [29] or comprehend a multi-floor subway station with multiple staircases and exits, two subway cars, various public passage areas, and several obstacles, covering a larger area of 14,000 m2 [23].

We observed a slightly higher prevalence of outdoor spaces, a trend is associated with the representation of large, real-world locations (Fig. 14).

We employed the term 're-created real-world' to describe the digital recreation of existing spaces. These recreations were mostly indoor spaces often depicting built infrastructure, although approximately one-third also related to outdoor areas. Slightly fewer occurrences (25 %) were categorized as 'fictional', indicating the digital creation of spaces that, while they may simulate typical existing spaces, are imaginary and do not realistically recreate any real-world location.

3.7. Limitations

More than half of the papers reviewed (n = 29) lacked a discussion on limitations, risks, or areas of caution. Among the publications that explicitly addressed limitations (Fig. 15), 22 % focused on the quality of the studies [61,67].

The concerns included the quality of results versus possible bias in some aspects of methodology (sample size, provenance of participants, etc.) [54], absence of a comparative framework [31], or the need to consider cross-cultural differences and prior exposure to disaster [69].

Regarding the limitations of technologies in disaster management, the digital and technological divide emerged as a significant issue. This divide affected both audience familiarization with new technologies [56,66] and access to them [41,59]. Technological limitations included hardware development bottlenecks, with VR-HMD display limitations for real-time rendering of spaces, especially large ones [35,39,43], and challenges related to network connectivity and coverage [46]. Hardware-related issues also included visualization strategies, such as VR rendering [25], optimal field of view [37], and a limited number of predefined environmental components [49] necessary for appropriate visualization of disaster spaces. Concerns about VR intensity and realism, including motion sickness, were also debated [28,68], with exposure to VR potentially causing motion sickness [28,39].

In addition to technological components, issues with participation were also noted (n = 4). Problems identified included the involvement in "participatory" urban planning sessions for disaster-prone areas [71]; the predominance of experts over victims in co-design sessions, which raised concerns about inclusivity [29]; and the need for larger and more diverse groups to adopt a more inclusive design process [29,30]. These participation concerns were also reflected in discussions about sample size from a methodological standpoint [54].

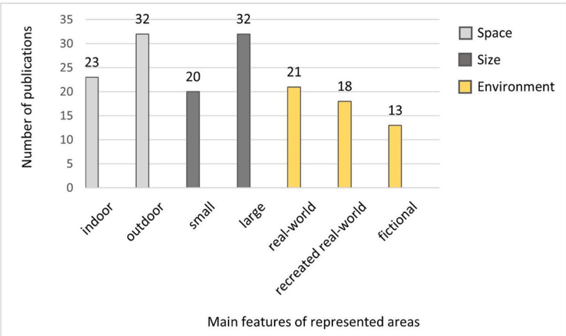

Fig. 14. Some key features of the areas represented.

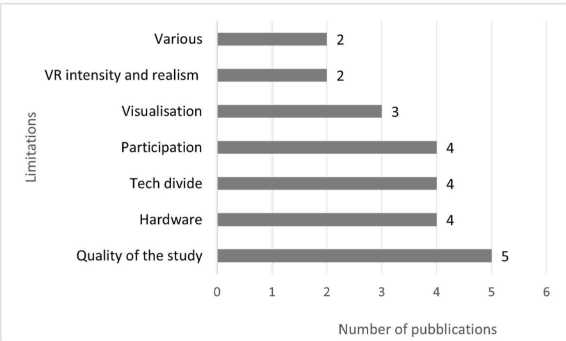

Fig. 15. Limitations of digital technologies.

4. Discussion

In this section, we summarize and discuss the overall findings of the review. Disasters triggered by natural hazards, such as floods, earthquakes, and cyclones, have been identified as the most extensively researched topic. During 2023, the increasing frequency of disasters affecting larger geographical areas and populations has seen a 10 % rise in occurrences and a 34 % increase in casualties over a twenty-year annual average [22]. This escalating global concern appears to serve as a catalyst, if not a contributing factor, motivating exploration of novel approaches to bolster the overarching system of disaster risk reduction and management. This observation aligns with a significant increase in publications published over the past two years, showing a five-fold increase. Additional data is necessary to confirm this trend.

A significant finding is the prevalence of Virtual Reality as the predominant digital technology, particularly in the field of Computer Science, encompassing various aspects of disasters and their places. VR is primarily evaluated for its practical utility as a potentially life-saving tool for preparedness, representing an asset for prevention efforts. Evidence suggests that VR-based training surpasses traditional methods in numerous scenarios, such as simulating evacuation processes [23,25,33,58] or educating individuals about earthquakes through VR-based simulations [28,31,59]. Similarly, Mixed Reality and Augmented Reality present distinct opportunities for evacuation drills [48], with their ability to overlay and integrate with real environments extensively explored [49]. Conversely, 360-degree technology was less utilized. Despite being considered an enhancer of realism, discussions regarding its efficacy in fostering empathy [66] continues. Coupling 360-degree media with VR solutions was found to facilitate immersion, enhancing a positive attitude towards the content [67]. The nexus between realism and effectiveness of VR needs further research, particularly regarding efficacy across different demographic and social groups [29]. This calls for the need to adjust exposure to VR flexibly, balancing the benefits of immersivity, -such as enhanced training, simulated disasters exposure, or the development of wayfinding skills for escape routes-against the risks of motion sickness [28,39] or potential psychological and physical discomforts. Another significant observation from the corpus is the association of technologies with specific phases of disasters, as dictated by their affordances. Although no clear pattern emerges, this association is noted in a limited subset of reviewed papers (n = 52). For instance, trainings and drills during the preparedness phase were more effective than 2D methods thanks to the ability of MR to superimpose additional visual information over reality [45,48]. Additionally, in large-scale environments such as urban flooding [51] or debris flow catchment studies [69], GIS-based solutions enhance situational awareness by processing large volumes of georeferenced data from aerial images.

Virtual Reality emerged predominantly in the context of preparedness, focusing on prevention by creating scenarios and virtual hypotheses that could be visually tested for drills, evacuation simulations, and training enhancements. The affordances of virtual systems tailored to specific training needs enable the production of digital experiences simulating events that are challenging to replicate in the real world, such as initial casualty responses [55], resulting in training modules with considerable potential [56]. Consistent with this finding, the primary impact assessed by the publications centred on improving safety behaviours and measures. In this field, the potential of VR is likely still largely untapped due to technological gaps and remains at experimental level. Hardware limitations for real-time rendering of spaces, especially large ones [35,39,43], the tech and digital divide [41,56,59,66], as well as access issues emerge as significant barriers for the adoption of this technology in real-world settings.

Interest in exploring digital avenues for capturing physiological signals and addressing psycho-emotional conditions surfaced cross-thematically in a limited but significant number of studies [39,58,72], indicating the potential of digital bio-signals in conjunction with multiple digital technologies as a promising area of inquiry. Our analysis identified its association with the response phase, with publications focusing on psychological aspects and psychobiological signals that could be digitally harnessed to enhance the well-being of rescuers [53]. There are multiple limitations to studying well-being. For instance, induced stress could differ accordingly to different simulation scenarios [39], and factors such as the complexities of real environments can impact stress levels, making it difficult to replicate the stress experienced in non-virtual situations. Additionally, from an ethical perspective, replicating extremely high stress would be highly questionable [25].

Digital mapping for spatial planning-driven actions often relied on Geographic Information Systems (GIS) technologies, leveraging their capacity to cover extensive areas, and serving as a crucial asset for emergency planners. These technologies were frequently associated with the recovery phase, reflecting their role in facilitating participation. The data related to digitally mapped information analysed in our review aligns with a series of publications emphasizing enhanced visualization, monitoring, and reporting to render data accessible, shareable, and reportable, representing one of the principal research interests identified in this review, after training. Moreover, insights from the review suggest the importance of considering a multimedia landscape where Extended Reality (XR) solutions coexist alongside traditional and emerging media, including social media [62,64], collaborative digital mapping, and crowdsourcing [65].

'Participation' as thematized in this publication constituted a limited category (n = 4), primarily associated with traditional media. This review reveals a notable lack of studies harnessing the potential of XR for participation, with exception of Zhang et al. [70]. Publications addressing 'participation' typically focus on real-world settings and events where communities heavily rely on digital solutions associated with the earlier waves of digital technologies, such as Geographic Information Systems (GIS) and, more recently, social media. While 360-degree media is occasionally linked to participation, it mainly appears in journalism studies [67,67]. The relatively sparse presence of this theme is reflected in the majority of studies being conducted with individual users rather than 'communities' or specific target groups. Most publications treat subjects as users (user-driven), viewing them as abstract entities and focusing on their cognitive and behavioural 'functionality, without considering factors such as sexual orientation, gender, age, educational level, occupation, etc. This approach overlooks the diverse demographic, personal, and sociocultural contexts and how it might influence how 'users' (people) interact with technology.

Some publications (n = 4) mentioned limitations on participation, citing challenges in participatory approaches [71]; issues of inclusivity [29]; and concerns about sample size and nature [54]. However, there was no broader discussion on defining the central role of participation.

It is crucial to note that most publications primarily focus on studies involving humans in controlled environments, as determined by the inclusion/exclusion criteria applied during publication selection. The studies mostly recreate disaster-prone areas or hypothetical scenarios, often lacking a direct correlation with real disaster settings. Some exceptions are linked to specific sectors, such as the reconstruction of the adobe citadel of Bam in Iran, destroyed by an earthquake, where VR and AR were used to promote a digital experience of the lost space [76], or the Rockaway peninsula, where digital activists employed crowdsourcing technologies to maintain the connection with their territories in response to the Superstorm Sandy [65]. Typically, computer science applied to disaster cycle management focuses on pre- or post-disaster scenarios, involving virtual simulations of various types of disaster settings. Despite the potential of VR and 360-degree imagery, few of the reviewed publications mentioned the impact of perceived realism on outcomes [68], nor did they indicate it as a potential area or limitation for future research initiatives. Actual digital replicas appeared only in the heritage sector [75], where simulated environments are more common [76].

Developing digital proofs of concept that explore the interactions between humans, the environment, and disasters is a highly complex and resource-intensive endeavour, often requiring multidisciplinary teams [25,39,48,50,55,71] and reliant on grant funding (67 % of the reviewed publications were funded by grants). This represents a significant limitation when considering the applicability of XR to disaster management. Extended Reality technologies require substantial resources, which limit the size, type, and level of detail of the spaces that can be digitally represented. Most studies involving VR/MR/AR, focus on small indoor environments, such as buildings. For larger-scale representations, researchers and emergency planners seem to prefer non-immersive digital technologies, such as GIS-powered tools. While VR seem effective for both indoor [27,60] and outdoor spaces [35,57], it proves effective in recreating small areas [26]. Limitations of VR technologies, mainly on rendering large scale areas are also acknowledged in some publications [35,39]. In contrast, GIS-powered environments are more effective on a larger scale [51,69] with challenges related to optimization of field of view [37].

Considering the ethical dimension associated with deploying digital technologies in disaster contexts, most research focused on preliminary and prototypical phases, with practical applications or early considerations of ethical and potential risks being uncommon.[3] Ethical concerns were rare. A few examples were related to questioning the replication of stress in a VR experiment simulating fire to assess selective attention in emergency wayfinding [25], or using VR-SG training for disaster risk mitigation while being aware of potential reduction in autonomy, minor health issues, or virtual realism. In one study [68], De Fino et al. demonstrated sensitivity to the identified ethical issue, specifically VR intensity and the associated risk of desensitization to real-life disasters, opting for designing a training module with an option for an immersive and non-immersive mode. Additionally, to mitigate the risks associated with superrealism -where phenomenological reality is indistinguishable from XR realities [77]- the authors opted for a typological, non-photorealistic though recognizable scenario for the VR-SG (Virtual Reality Serious Game). It is evident that ethical issues, far from being absent, represent an aspect whose consideration will increase as VR devices development and integration with high-speed network coverage expand.

5. Conclusions

In this paper, we conducted a scoping review of how digital technologies such as VR, AR, MR, and combined XR are utilized for disaster management across different phases of the Hazard Management Cycle. We focused on publications dealing with ‘place’ as human/environment nexus. Disasters often alter or destroy these ‘humanified’ spaces, yet they also present an opportunity to channel resources for rebuilding into participatory and people-centred placemaking. This approach aims to 'bounce back (places) better', potentially decreasing displacement and fostering community resilience. In the papers reviewed, community resilience was primarily viewed through a socio-economic lens, with traditional media environments, including social media, examined for their role in connecting and mobilizing communities. In contrast, within the context of XR technologies applied to disasters, resilience was more frequently regarded as a crucial aspect of preparedness. This highlights the complex, cross-disciplinary nature of the term, emphasizing its polysemy and underscoring the need for caution in its application. Further research is necessary to specifically explore the nexus between XR and resilience, which extends beyond the scope of this article.

In our scoping review VR emerged as the most prevalent technology used in place-centric research within disaster contexts (RQ1). One of its most outstanding features is the capacity to let individuals experience situations or explore settings that are unlikely to be encountered in the real life. VR is extensively studied for training emergency responders and communities by simulating various disaster scenarios, including evacuation drills, emergency response exercises, and decision-making training. Additionally, VR simulations help to study the management of the psychological impact of disasters, such as stress and anxiety during emergencies. For example, VR can simulate earthquakes to assist individuals in managing and regulating anxiety. These immersive experiences are difficult to replicate in real life and significantly enhance understanding of disaster risks and critical safety measures. Together with AR and MR, VR is also studied for the potential in assessing and monitoring damage during and after disasters, providing accurate and timely information to aid in recovery efforts. The reviewed studies predominantly emphasize the technical and practical applications of VR

[3] Recently, we have seen a surge of ethical debates about AI as it becomes more central to our everyday lives, with billions of users and thousands of companies massively using AI-based application on daily basis. A search on July 26, 2024, for scientific articles on Google Scholar returns 11.400 results for “AI Ethics” in 2023, as compared as 1300 in 2019. Conversely, XR technologies and metaverse are still under development. It is no surprise that the impact of XR technologies on disasters is potentially perceived as long-term goal, despite calls for convergence between the academic and professional worlds from international agencies.

technologies for improving evacuation processes, enhancing situational awareness, and supporting decision-making. Yet, few studies explore how these technologies can address the emotional and psychological aspects of disaster recovery. This gap is particularly evident in the context of place-centric research, where the loss of place and environmental trauma significantly impact the well-being and resilience of affected communities.

Regarding the assessment of a potential association with specific phases of the Hazard Management Cycle (RQ2), it is important to note that many technologies were used or studied for potential use in multiple phases of a disaster. Rather than identifying a clear trend, we highlight observations based on how we assigned these technologies to a primary phase of the Hazard Management Cycle during data extraction. Our main takeaway is the potential of virtual technologies to enhance disaster preparedness. This finding aligns with the prevalence of VR technology, whose main affordance is immersive simulations of disaster scenarios. Technologies are generally associated with phases of the HMC based on their affordances. For instance, in large-scale environments, GIS-based solutions process large volumes of georeferenced data from aerial images. Consequently, this technology is frequently associated with the recovery phase, as it can be easily employed as a visualization and planning tool.

Although no specific dynamics could be detected for technology deployed within the response phase, possibly due to the necessity to rapidly deal with contingent factors in varied contexts, some publications (n = 3) presented devices capable of capturing physiological signals. These devices point to applications addressing the psycho-emotional conditions of both rescuers and disaster victims, representing an interesting avenue for further research for scholars aiming at connecting with the topic of environmental trauma and showing concern for victims and rescuers wellbeing. One way to harness the power of biosensors and integrate them into XR research is to use them to measure the differences in physiological signs of wellbeing and discomfort between experimental scenarios and real-world cross-cultural contexts. This approach will yield more knowledge on the nature of superrealistic feelings and emotions, which in turn could inform research on disaster trauma recovery supported by XR technologies.

Lastly, community participation and integration were rarely identified as a focus in the reviewed studies addressing the technical deployment of digital technologies in disaster management (RQ3). A limitation noted in the reviewed literature was that the research mostly involved a restricted number of individuals rather than groups, who were often simply identified as users of the experience. This approach was chosen to adjust for technical limitations or to study outcomes, rather than involving these individuals in designing, defining, and deploying the technologies. In addition, the complexity of innovative technological interventions poses problems of accessibility and sustainability, partly contributing to the absence of social groups and community involvement.

Future research should prioritize the exploration of how VR, MR, AR, combined XR, and other digital technologies can be utilized to support psychological recovery and trauma alleviation in disaster-affected populations. Scholars should investigate methodologies for integrating social dimensions and community presence in disaster management using immersive XR technologies. These studies should involve communities in the design, deployment, and evaluation of these technologies to ensure accessibility and sustainability.

Understanding the human experience and the social dimensions of disaster management is crucial for developing comprehensive strategies that address both the immediate practical needs of individuals and support long-term community resilience and well-being. The dynamics of continuous border-crossing between online and offline realities, facilitated by social media and crowdsourcing of spatial information, highlight the importance of community presence in this process. As we increasingly transition toward immersive online environments, properly framing and understanding the role of communities will become even more critical. This calls for strategies that integrate the social dimensions associated with new immersive XR technologies. The VR experiences that have been particularly employed to support specific phases of DRRM are still very often individual experiences. This is due both to the greater resources needed to enable multiple people to participate simultaneously, in terms of the number of visualization hardware required and the resources needed to render large enough areas in real time where interactions are possible. From studies designed with simultaneous multiple participation, useful insights are expected to emerge that will help us better understand how to develop virtual reality as a social space.

While our review uncovers first observations in the use of place-centric XRs for disaster management, there, we propose several specific recommendations for future research development on this area:

A crucial area of focus should be on how immersive XR technologies can support post-traumatic recovery in disaster-affected populations. Such studies should be in-depth, and longitudinal, as they have to take into account the phases of recovery post-trauma (phases that go from the moment of the disaster, to the long-time of reconstruction and recovery). Such studies could significantly enhance processes of community resilience, especially in times of post-disaster displacement.

Another important direction should be on how these technologies could be co-designed based on value-led design thinking approaches, to foster community participation in disaster management. This would ensure that the technological solutions are embedded in the specific socio-cultural contexts they would like to serve.

Studies exploring the socio-cultural potential of place-centred XR technologies should also address cross-cultural and demographic variations in the effectiveness and acceptance of XR technologies in disaster management. Ideally, this should be done through a qualitative approach utilizing ethnographic methods, focus groups, and semi-structured interviews. Understanding these variations can lead to more effective and inclusive disaster management strategies, enhancing the acceptance and efficacy of XR technologies across different communities.

Another promising area of development that seems to emerge from our findings is linked to the study of realism and immersion (i.e., sense of presence) and their efficacy in the areas of training for disaster preparedness, as well as of post-disaster reconstructions for population recovery. Experimental studies comparing different levels of immersion, such as VR versus AR, and their effects on user engagement, knowledge retention, and behavioural change can provide valuable insights. Eye-tracking, physiological, and neurological monitoring can offer objective data on these effects.

These recommendations build directly on our major findings, which highlight the potential, and some of the strengths and limitations of XR technologies in disaster management. By pursuing these future research directions, we can address the identified gaps and continue to investigate the socio-cultural potential of XR technologies to enhance disaster management practices.

CRediT authorship contribution statement

Matteo Baraldo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paola Di Giuseppantonio Di Franco:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

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

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