Stakeholder analysis in the application of cutting-edge digital visualisation technologies for urban flood risk management: A critical review

Expert Systems With Applications 236 (2024) 121426

Contents lists available at ScienceDirect

Expert Systems With Applications

journal homepage: www.elsevier.com/locate/eswa

Review

Stakeholder analysis in the application of cutting-edge digital visualisation technologies for urban flood risk management: A critical review

Vahid Bakhtiari [a], Farzad Piadeh [b,c], Albert S. Chen [d], Kourosh Behzadian [b,e,*]

[a] Civil and Environmental Engineering Department, Amirkabir University of Technology, Hafez St., Tehran 15875-4413, Iran
[b] School of Computing and Engineering, University of West London, St Mary's Rd, London W5 5RF, UK
[c] School of Physics, Engineering and Computer Science, University of Hertfordshire, Hatfield AL10 9AB, UK
[d] Centre for Water Systems, Faculty of Environment, Science and Economy, University of Exeter, Exeter EX4 4QF, UK
[e] Department of Civil, Environmental and Geomatic Engineering, University College London, Gower St, London WC1E 6BT, UK

A R T I C L E I N F O

Keywords:
Augmented reality
Digital twin
Flood risk management
Mixed reality
Stakeholder analysis
Urban flooding
Virtual reality

A B S T R A C T

Cutting-edge flood visualisation technologies are becoming increasingly important in managing urban flood risks, particularly from the perspective of stakeholders who play a crucial role in controlling and reducing the risks associated with flood events. This review study provides a comprehensive overview of stakeholder analysis in this context, highlighting gaps in current research and paving the way for future investigations. For this purpose, scientific literature and critical analysis are conducted based on identified relevant research works to map the mutual role of stakeholders in this context. This study categorises cutting-edge technologies into four groups - virtual reality, augmented reality, mixed reality, and digital twin - and explores their adoption in engaging various stakeholders across the five key stages of risk management: prevention, mitigation, preparation, response, and recovery. Results show that existing research has primarily concentrated on the support to water utilities and the communication with the general public. However, there is a noticeable gap in research regarding the comprehensive engagement of important stakeholders such as policy-makers, researchers, and insurance providers. Furthermore, the study highlights disparities in the involvement of stakeholders in damage assessment studies, particularly with a lack of representation from policy-makers and researchers. Finally, the study introduces the concept of overlooked key stakeholders and the interconnected impacts they have, which has received relatively little attention in previous research.

1. Introduction

Climate change has emerged as a significant driver of global temperature rise, which has contributed to the alteration of weather patterns across the world. As a result of these changes, certain regions have experienced a surge in precipitation intensity and the frequency of extreme rainfall, primarily in urban areas (Woolway et al., 2020). The amplified rainfall in urban settings, specifically those that lack adequate storm water management infrastructure or efficient drainage systems, has led to a variety of negative outcomes, with flooding being the most consequential (Piadeh et al., 2022a). Urban flooding can have far-reaching impacts on both physical infrastructure and the well-being of urban inhabitants. Floodwaters can lead to structural damage, weakened foundations, and clogged drainage systems, as well as soil erosion, leading to harm to critical infrastructures such as roads and bridges (Piadeh et al., 2023).

On the other hand, the social impacts of urban flooding are numerous, affecting the health and safety of residents. Flood can be forceful and dangerous, sweeping away people and properties, causing drowning and other water-related injuries (Bakhtiari et al., 2023). They can pose a public health threat by carrying sewage (for the case of combined sewer overflows), chemicals, and other hazardous materials, which can result in outbreaks of waterborne diseases. The psychological impact of flood is also noteworthy, causing emotional distress and long-lasting effects (Sarmah et al., 2020). While numerous sustainable solutions, especially non-structural, have been developed to tackle the challenges of urban flooding, the involvement of stakeholders is critical for their success (Rafiei-Sardooi et al., 2021). Stakeholders including policy and decision makers, operators and industries, researchers and developers, and affected population not only bear the brunt of urban

* Corresponding author at: School of Computing and Engineering, University of West London, St Mary's Rd, London W5 5RF, UK.
E-mail addresses: farzad.piadeh@uwl.ac.uk (F. Piadeh), a.s.chen@exeter.ac.uk (A.S. Chen), Kourosh.behzadian@uwl.ac.uk (K. Behzadian).

https://doi.org/10.1016/j.eswa.2023.121426
Received 14 June 2023; Received in revised form 29 August 2023; Accepted 1 September 2023
Available online 4 September 2023
0957-4174/

flood damages but also play a crucial role in addressing the associated risks. Effective stakeholder engagement ensures that all perspectives are considered, resources are utilised effectively, and the needs of vulnerable populations are addressed adequately (Geaves and Penning-Rowsell, 2016). Collaborative efforts and consensus-building among stakeholders facilitate the development and implementation of flood risk management programmes that promote the long-term health and resilience of communities.

Cutting-edge flood digital visualisation technologies (CEVT), which entails computer-based tools to create visual representations of flood risks, vulnerabilities, and potential impacts, represents a potent strategy for enhancing stakeholder engagement in flood risk management, especially through virtual reality (VR), augmented reality (AR), mixed reality (MR), and digital twin (DT) as illustrated in Table 1 (Macchione et al., 2019; Allam et al., 2022; Bakhtiari et al., 2023). More specifically, VR technologies allow users to enter a computer-generated 3D environment and better comprehend the potential impacts of flooding (Carneiro et al., 2018). Immersive 3D images provide a realistic and interactive experience, and 3D web-based visualisation refers to the use of 3D digital models and interactive technology on web platforms are the two initial application of VR technologies (Singh and Garg, 2016; Burian et al., 2020). Furthermore, the immersive dynamic VR environment offers users a realistic and immersive experience to explore and comprehend flood events and their consequences in a controlled and safe manner (Luo et al., 2021). Finally, Game-based VR incorporates elements of gameplay to create a more immersive environment, aiding users in understanding complex flood scenarios and their consequences (Simpson et al., 2022).

AR overlays digital information onto the real world, providing stakeholders with a view of the potential impacts of flooding in their real-world surroundings (Qamar et al., 2023). Two main approaches including mobile phone apps and computer software are identified in the context of flood visualisation. Mobile apps utilise the device's camera and sensors to display real-time flood information, such as water levels, on top of a live video feed of the affected area (Haynes et al., 2018). Computer software platforms enable the creation of customised AR applications using touch tables or physical replicas (Tomkins and Lange, 2019). MR technology enables the creation of immersive flood visualisation experiences that merge the physical world with digital content, allowing users to interact with the digital elements (Haynes and Lange, 2016). Finally, DT facilitates the creation of a virtual replica of a real-world system or environment. It creates a virtual model of the system by integrating data from various sources such as sensors, weather forecasts, and urban maps to build prototype or living platform for stakeholders (Pedersen et al., 2021).

The integration of cutting-edge technologies has been shown to enhance stakeholder engagement in flood risk management, resulting in improved preparedness and resilience in the face of flooding events.

Table 1
Definitions, similarities, and differences between the four cutting-edge digital flood visualisation technologies within the context of flood management.

Technology	VR	AR	MR	DT
VR	Replicating the physical asset of urban areas to simulate flood events and their impacts in the virtual space	VR provides a fully immersive and controlled environment, but AR enhances real-world experiences and on-site facilitates	Users can freely explore within the VR environment, but MR allows users to navigate freely within the physical urban environment while still interacting with the augmented flood visualisations	VR focuses mainly on creating immersive experiences, but DT incorporates real-time data from monitoring systems to create a dynamic and updated representation of the urban area
AR	Contributing to a better understanding of flood events within their spatial virtual context	Overlying digital information onto the real world to provides users with a view of the potential impacts of flooding in their real-world surroundings	AR overlays virtual elements onto real-world environment to provide realistic flood impact observation, but MR combines virtual elements with real-world environment to interact with physical and virtual elements simultaneously	AR maintains the context of physical environment by providing additional digital information, but DT takes it a step further by capturing the behaviour of the physical urban environment
MR	Creating a realistic sense of flood occurrence	Allow users to navigate through the urban area, changing viewpoints, and interact with virtual flood visualisations or data overlays	Overlaying flood-related data onto the real-world environment to allow users to interact with the physical surroundings	MR blends virtual elements with the real-world environment, but DT captures and simulates the actual urban environment
DT	Enhancing the understanding of complex relationship of flood dynamics and urban elements	Integrating real-time data into the visualisation process	Providing actual urban settings, considering physical characteristics and spatial relationships of urban elements	Creating a virtual replica of a real-world urban area by capturing both physical and functional aspects of the urban environment for flood simulation

Definition Differences Similarities

However, there is a few comprehensive and critical research on the application of these technologies in the context of stakeholder engagement across all stages of flood risk management. Several articles have directed their attention towards incident response measures and the involvement of some stakeholders including decision-makers, local authorities, technical staff, and emergency service providers (Wolf et al., 2022). Their collective responsibilities encompass tasks such as acquiring geographical data pertaining to the incident, identifying the nearest responder to the incident site, determining the optimal route using traffic data, and facilitating communication with other emergency services. Conversely, other articles have sought the engagement of policy-makers, urban designers, and researchers in the implementation of flood mitigation measures during the stages of urban planning and design, utilising cutting-edge technologies (Langenheim et al., 2022). Alternatively, some articles have primarily focused on local communities and the affected population, aiming to enhance their awareness of pre- and post-disaster risk measures through the utilisation of CEVT (Kundu and Nawaz, 2019: Gamberini et al., 2021).

However, despite the valuable contributions made by various research works as outlined above to engage stakeholders in flood risk management through implementing cutting-edge technologies, there is a lack of comprehensive investigation of all relevant stakeholders across the entire spectrum of flood risk management. Urban flood risk management involves a wide range of actors beyond the above-mentioned groups who plays a vital role in mitigating and responding to urban flood risks, and their collective efforts are integral to achieving effective outcomes. Moreover, flood risk management is continuous and iterative endeavour that encompasses various phases and hence focusing solely on a particular stage limits the understanding of the holistic dynamics and interdependencies among different components within the flood risk management framework. Thus, a more inclusive approach that acknowledges the multitude of stakeholders involved and encompasses the entire risk management continuum is necessary to fully evaluate the effectiveness, applicability, and limitations of these technologies in real-world scenarios.

Therefore, this study aims to provide a holistic and critical overview of the role of stakeholders in studies implementing CEVT throughout urban flood risk management stages. By taking this approach, the study also aims to answer the following key research questions (RQ):

- (RQ1): Which stakeholders are encompassed in CEVT studies and what are their roles?
- (RQ2): Which specific CEVT are utilised for each group of stakeholders?
- (RQ3): How stakeholders are involved in the various risk stages?
- (RQ4): What key stakeholders have not been included in the CEVT studies?

Furthermore, despite the crucial roles of various groups of stakeholders involved in flood risk management and their potential impacts on, or susceptibility to, the influence of flood visualisation, the extant literature in this domain has primarily focused on a limited subset of stakeholders. This limited focus raises concerns regarding the potential oversight of crucial perspectives and insights in flood risk management. Such omissions can lead to incomplete or biased assessments of flood risks, inadequate consideration of social, environmental, and economic factors, and a lack of support from excluded stakeholders. As such, this study aims to highlight those stakeholders who have been traditionally overlooked or underrepresented in the applications of digital technologies for flood management and flood digital visualisation. This study also investigates how these neglected stakeholders can be effectively engaged and integrated into the process, ensuring their voices are heard and their needs are considered.

2. Research scope and design

Following the guidelines recommended by Moher et al. (2009), the search strategy encompassed searching for the relevant keywords in titles, abstracts, and keywords of the research studies documented in Scopus search engine (see S_1 in Table 2). This approach allowed for a comprehensive exploration of the literature. To refine the search results and ensure the inclusion of pertinent studies, a series of four search and screening strategies (S_2-S_5 in Table 2) were sequentially applied. Each strategy aimed to progressively narrow down the pool of publications, ensuring the selection of high-quality and relevant studies. After meticulous screening and rigorous evaluation, a final set of 43 studies (See appendix for RIS file of used database) were deemed suitable for further analysis. It is noteworthy that the initial search yielded a considerable number of publications, with 891 articles identified in the first stage (S_1). However, through the subsequent stages (S_2 and S_3), the search results were refined, allowing for a more focused and specific selection process. The selected studies underwent another round of screening, specifically targeting the application of data presentation techniques. This process aimed to identify studies that incorporated CEVT approaches for urban flooding. i.e., VR, AR, MR, and DT.

Subsequently, investigation into the contributions of various stakeholders in the domain of digital visualisation of urban flooding (S_4) was undertaken, drawing from the recommendations made by Piadeh et al. (2022c) for classifying stakeholders into three primary categories: policy-makers, CEVT developers, and CEVT users. Following this categorisation, the stakeholders discussed in the 43 selected articles were identified, tracked, and analysed to address RQ1. The types of stakeholders were determined, along with their respective sub-categories. The identified stakeholder categories include water utilities, which

Table 2
Flowchart of the search strategies in the study.

Code	Search and screen strategy	Keywords	Selected research works
S_1	Finding publications studying urban flooding based on searching in titles, abstracts, and keywords	(Urban OR City OR Domestic) AND (Flood OR Pluvial OR Fluvial OR Storm OR (Extreme AND Weather)) OR (Runoff OR Overflow OR Discharge OR Inundation OR Susceptibility)	891
S_2	Results were limited to the last decade, English language articles, and journal papers only with searching under titles, keywords, and abstracts.	–	193
S_3	Results were screened for application of data visualisation or data presentation research works.	(Augment OR Virtual OR Mixed) AND (Reality) OR (Digital AND Twin)	43
S_4	Results were screened for stakeholder identification. Stakeholders are identified	(Authority OR ((Decision OR Policy) AND Maker) OR Politician) OR (People OR Citizen OR Academic OR (Affected AND population) OR Representative) OR (trustee AND Board) OR Community) OR (Operator OR Expert OR Engineer OR Technician) OR (Business OR Industry OR Commercial)	42
S_5	Results were screened for finding risk management stages. Stages are identified	(Prevention) OR (Mitigation) OR (Preparedness) OR (Response) OR (Recovery)	41

encompass decision-makers and technical staff; policy-makers; researchers; the public, consisting of representative boards and affected populations; and insurance providers. It is pertinent to mention that the roles and responsibilities of all recognised stakeholders are further elaborated upon in Section 4. Furthermore, an analysis of the research works pertaining to various stages of flood risk management (S_5) was conducted, following the recommendation made by Bhaduri (2019) in which distinct stages of risk management are characterised by specific features. In line with these features, the flood risk management approaches discussed in the 43 selected articles were mapped into the stages elucidated by Bhaduri (2019). It was observed that the selected research works encompassed five key stages: prevention, mitigation, preparedness, response, and recovery. Further discussion on this risk management stages are provided in Section 5.

To identify relevant studies, the current study specifically focuses on urban flooding and hence excludes other forms of flooding, such as flooding from non-urbanised rivers, dam breaks, lake, or wetland overflow. However, relevant cases outside of urban areas are considered to incorporate new ideas and concepts that may be useful for identifying gaps or suggesting future directions. These resources are used to demonstrate the gaps and potential stakeholder engagement in Section 5. Furthermore, this study incorporates other relevant information sources including documents related to project management, and stakeholder engagement, drawn from various industries and their respective databases. However, while it is acknowledged that numerous recent advancements are being implemented at an industrial scale by municipalities, water companies/utilities, and regional and national agencies, these developments may not be publicly available in detail. Consequently, tracking all necessary information from these advancements can be impossible and thus, this study is constrained to relying on published journal or conference papers only.

3. Research framework and structure

Stakeholder analysis in the context of applying CEVT for urban flood risk management is referred to the process of recognising, role mapping, and classifying individuals, groups, or organisations with a vested interest or influence in the implementation and outcomes of these technologies (inspired by Masalegooyan et al., 2022). This analysis facilitates an understanding of the stakeholders' perspectives, roles, requirements, and potential impacts on the project, thereby promoting effective engagement and collaboration throughout the development and implementation of these technologies for urban flood risk management.

Accordingly, the interactions among recognised stakeholders with CEVTs through various stages of flood risk management are outlined in Fig. 1. The complexity of Fig. 1 makes it challenging to analyse and identify the interrelationships among stakeholders, technologies, and risk management stages. Hence, this study adopts a three-level framework for conducting a stakeholder analysis in a more comprehensive manner. The first level, corresponding to RQ2, delves into the intricate dynamics between CEVT and the recognised stakeholders. This aspect, which is comprehensively explored in Section 5, delves into investigating how these CEVT have effectively engaged stakeholders to address specific objectives within the realm of flood visualisation.

The second level, discussed in Section 5, focuses on mapping the roles of stakeholders onto the flood risk management stages to address RQ3. This involves identifying the responsibilities, interests, and concerns of each stakeholder group throughout the entire process. Finally, the third level deals with addressing RQ4 to identify overlooked stakeholders and their mutual impacts on CEVT. For this purpose, this study draws upon inspiration from similar works including but not limited to Piadeh et al. (2022c) for adopting a scientific literature review methodology to systematically identify neglected key stakeholders and analyse their roles and mutual impacts in the context of cutting-edge technologies. This approach recognises that a comprehensive understanding of stakeholders extends beyond the confines of a specific field and requires a broader exploration of relevant literature. The scope of the literature review in this study is expanded to encompass not only articles within the field of flood visualisation, but also scientific reports, guidelines, and publications from diverse industries, such as non-urban flood management, project management, and stakeholder engagement. By incorporating these additional sources and drawing upon various industry-specific databases, the study aims to capture a more comprehensive perspective on neglected stakeholders and their significance in advancing cutting-edge technologies. This multidisciplinary approach

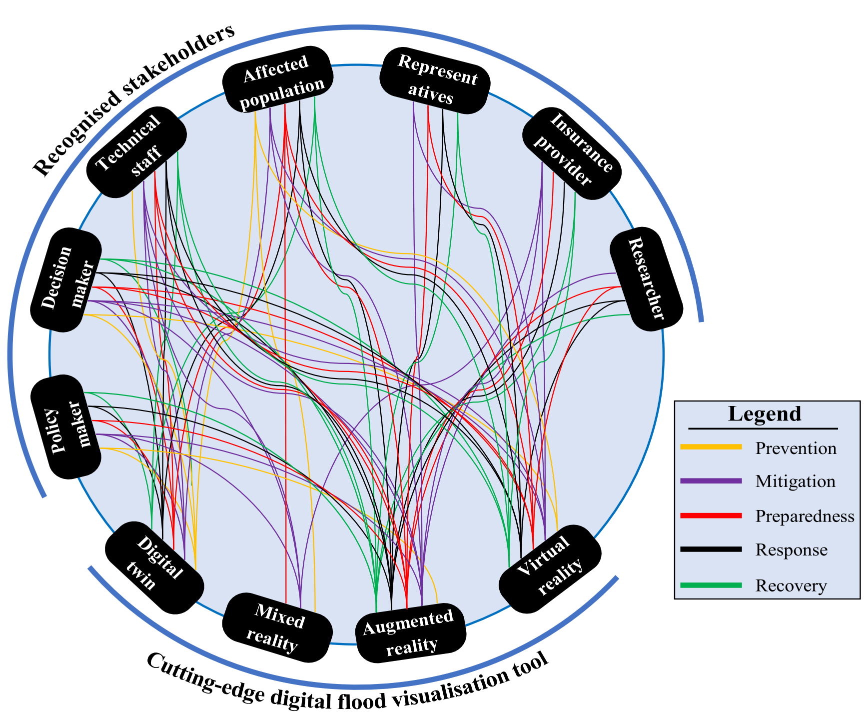

Fig. 1. Interaction map of different recognised stakeholders on data visualisation based on different flood risk management stages.

allows for a nuanced analysis of stakeholder dynamics and facilitates the identification of potential synergies and areas for improvement in flood risk management practices.

4. Recognised stakeholders

Table 3 presents an overview of the key stakeholders and their roles and responsibilities involved in CEVT. The five recognised stakeholder groups include water utilities, policy-makers, researchers, public, and insurance providers. The water utilities group encompasses decision-makers and technical staff, while the public group comprises representative boards and affected populations.

Table 3
Primary relevant stakeholders recognised in flood visualisation studies.

Recognised stakeholders	Roles/Responsibilities	Reference
Water utilities	Participating in flood-related initiatives, aiming to minimise the impacts of flooding on communities and ensure the reliable provision of water services	Pedersen et al. (2022)
Decision-makers	Formulating flood risk management plans that encompass structural and non-structural measures, align with allocating the necessary resources and funding to implement these strategies effectively	Amirebrahimi, Rajabifard, Mendis, & Ngo (2016)
Technical staff	Ensuring flood control systems are operational and effective in safeguarding people and property and monitoring flood situations and environmental conditions that can impact system performance	Schröter *et al.* (2017)
Public	Consisting of individuals who reside in flood-prone areas or have a stake in flood risk management, being able to actively participate in flood risk management processes by providing input on policies and strategies	Li et al. (2022)
Affected population	Individuals and communities directly impacted by flood events, possessing valuable local knowledge and expertise regarding flood risks, historical patterns, and community-specific vulnerabilities.	Burian et al. (2020)
Representatives	Composing of elected or appointed representatives accountable to the public, ensuring that flood risk management policies and practices are responsive to community needs and priorities	Jacquinod and Bonaccorsi, (2019)
Policy-makers	Developing policies, regulations, guidelines, and procedures that influence the actions and decisions in flood risk management	Truu et al. (2021)
Researchers	Conducting studies and investigations to gather data on various aspects of flood risk, developing sophisticated models and tools to simulate and predict flood events, and assessing the consequences of floods	Li *et al.* (2015)
Insurance providers	Offering financial protection, promoting risk reduction measures, conducting risk assessments, sharing data and expertise, and supporting recovery efforts to mitigate the impact of floods on individuals, insurance providers, and communities.	Mirauda et al. (2018)

4.1. Contribution analysis of recognised stakeholders in flood visualisation studies

According to the selected research works, the contribution of the recognised stakeholders in cutting-edge flood visualisation studies can be highlighted in Fig. 2. Water utilities hold the largest share of 44%, indicating their significant involvement and valuable input in terms of data, expertise, and practical insights. The public group follows closely with a 35% share, highlighting the importance of incorporating the perspectives and experiences of the society members. Policy-makers contribute 10%, researchers 7%, and insurance providers 4%, showcasing their respective roles in advancing flood visualisation practices. Further analysis within the water utilities group reveals that decision-makers account for 71% of the contribution, while technical staff make up 29%. In the public group, the majority of the contribution comes from the affected population (79%), with representatives accounting for 21%. These findings highlight the collaborative efforts of stakeholders in flood visualisation studies, showcasing their diverse contributions towards advancing the field and improving flood risk management strategies.

The largest share of water utilities, who play a vital role in safeguarding communities, reveals that it is imperative for them to utilise cutting-edge digital technologies efficiently in addressing the challenges presented by flooding. The prominence of decision-makers in these studies can be attributed to their responsibilities and decisions which have a significant impact on the success of these initiatives, thereby making their perspectives and insights crucial in comprehending the challenges and opportunities of CEVT. Although the insights and perspectives of operators are crucial for the successful implementation of CEVT for flood visualisation, their role is often more practical and less strategic than that of decision-makers (Pedersen et al., 2021). Hence, their share in studies related to the use of such technologies in flood risk management is lower than that of decision-makers.

As illustrated in Fig. 2, the public group which accounts for 35% of the focus, is placed as a second rank. The great emphasis on this group is a result of the growing recognition of the importance of engaging them in effective and sustainable flood risk management efforts, and the potential benefits of employing cutting-edge technologies to facilitate such engagement (Li et al., 2022). These studies have predominantly targeted the affected population within the public group, comprising 79% of the focus. This is because the ultimate objective of flood risk management is to protect and benefit stakeholders who are the most vulnerable to flooding impacts. Thus, comprehending their viewpoints, requirements, and concerns is crucial in developing effective digital visualisation methods and flood risk management strategies (Schröter et al., 2017). In contrast, representatives account for 21% of studies, suggesting a more specialised or narrow perspective on flood risk management. Although

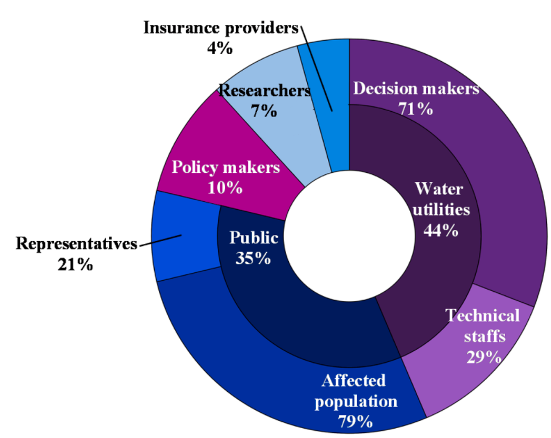

Fig. 2. Contribution percentage of the recognised stakeholders in the studies of cutting-edge visualisation technologies applied to flood risk management.

their perspectives and insights are valuable, they may not always reflect the broader concerns and needs of the affected population (Li et al., 2022). Therefore, studies that focus on the public group prioritise affected population perspectives and insights over representatives.

The relatively low presence of policy-makers at 10% can be attributed to their macro-level perspective on flood risk management. This group may not be directly involved in the implementation of digital technologies for flood risk management, which is usually an operational and tactical concern. Besides, the 7% representation of researchers in flood visualisation studies suggests that the specific research studies may have prioritised practical applications and immediate needs related to flood risk management over academic engagement. Collaborative efforts may have primarily involved other stakeholders such as government agencies that possess a direct role in implementing flood mitigation strategies, thereby resulting in a narrower emphasis on academic involvement (Ghaith et al., 2022). The lowest percentage of insurance providers (4%) can be attributed to the predominant involvement of academic or governmental institutions in the research conducted in this domain, which may not possess direct links to the private sector. Moreover, institutional, or regulatory barriers may limit this group's engagement in flood risk management through the utilisation of cutting-edge digital technologies (Mirauda et al., 2018).

4.2. Timeline contribution analysis of recognised stakeholders in flood visualisation studies

The information pertaining to the contribution of the recognised stakeholders in flood visualisation studies over the past decade is presented in Fig. 3. Overall, this Figure provides insights into the emphasis placed on various stakeholder groups across these years, thereby demonstrating a notable shift in the recognised target audience for further analysis during this period. Initially, the primary emphasised key groups were decision-makers, technical staff, and affected population. The inclusion of these stakeholders reflects their fundamental roles in shaping decision-making processes. Involving decision-makers allows for their perspectives and priorities to be incorporated into the visualisation process. This helps ensure that the resulting visualisations align with the strategic goals and objectives set by decision-makers (Sun, Puig, & Cembrano, 2020). Technical staff involvement is crucial as they contribute valuable insights into the technical aspects of flood management. Their expertise ensures that the visualisations accurately represent the physical aspects of floods, enabling more informed decision-making (Macchione et al., 2019).

Finally, engaging the affected population allows for a better understanding of their vulnerabilities, perceptions, and preferences in flood risk management strategies. By involving them, the selected research works can foster participatory approaches and empower communities to contribute to decision-making processes, ultimately leading to more

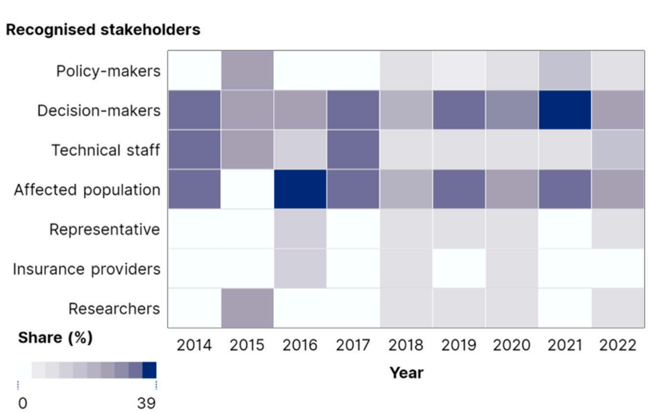

Fig. 3. Heat map for the contribution of recognised stakeholders in cutting-edge flood visualisation studies over the last decade.

inclusive and community-centred flood risk management solutions (Fu et al., 2021). The involvement of stakeholders in selected research works has been a consistent approach, with decision-makers and technical staff being regularly targeted. However, there is no unanimous agreement regarding the inclusion of the affected population. While significant attention was given to the affected population in certain years e.g., 2016, 2017, 2019, or 2021, this focus waned in other years over the past decade, such as 2015 and 2018. These highly variable changes show the absence of a definitive consensus within research communities regarding the significance of including the affected population as crucial stakeholders. In other words, while researchers tend to develop strategies for decision-makers, the affected population has often been viewed as victims rather than contributors for finding solutions.

This focus have expanded recently to include four additional groups: policy-makers, representatives, insurance providers, and researchers. The broadening of the focus through last decade reveals a more comprehensive and inclusive approach to these studies, aligning with the principles of integrated and participatory flood risk management. By involving all the mentioned stakeholders, selected studies can benefit from various perspectives, interdisciplinary collaboration, and broader landscape of flood risk management (Zhang et al., 2020). This approach promotes holistic understanding, transparency, equity, informed decision-making, and the development of effective risk management strategies and provides valuable insights into emerging trends, technological advancements, and best practices in flood risk management, fostering innovation and evidence-based decision-making.

5. Technology-based role mapping

5.1. Contribution analysis of recognised stakeholders across cutting-edge technologies

The primary goal of this investigation is to delve into the multifaceted involvement of diverse stakeholders in the utilisation of CEVT, as indicated in Fig. 4. Overall, flood visualisation studies have demonstrated a concerted effort to leverage these cutting-edge technologies for engaging stakeholders in the realm of flood risk management. However, despite these endeavours, notable research gaps persist, particularly concerning the adoption of VR for policy-makers and the utilisation of MR and DT technologies by representatives and insurance providers. These gaps highlight the imperative for further exploration and investigation to bridge these knowledge voids. Additionally, in the landscape of flood visualisation studies, the prevailing emphasis has been on the involvement of decision-makers and the affected population through the application of the VR technology.

Fig. 4 also reveals that AR, MR, and DT have been more frequently explored in relation to policy-maker engagement as they offer unique opportunities for policy-makers by providing a realistic and dynamic representation of flood scenarios, enabling them to gain a deeper understanding of the potential impacts and exploring various mitigation strategies (Li et al., 2015; Truu et al., 2021). On the other hand, the absence of research works exploring policy-maker engagement in VR-based studies suggests a literature gap and an opportunity for future research. Understanding how VR can be effectively utilised to engage policy-makers, and how it can enhance their decision-making process in flood risk management, would be valuable for advancing the field.

Moreover, the preference VR in engaging decision-makers may stem from the immersive characteristics of this technology, which have the potential to enhance decision-makers' spatial cognition and foster an intuitive understanding of flood risks (Wang et al., 2019). Furthermore, VR offers a shared visual platform that facilitates collaborative decision-making processes, allowing stakeholders to collectively discuss various flood management options. Besides, involvement of technical staff using cutting-edge technologies has been relatively limited, as evidenced by the sparse number of articles specifically addressing their participation. This observation highlights a potential gap in the literature concerning

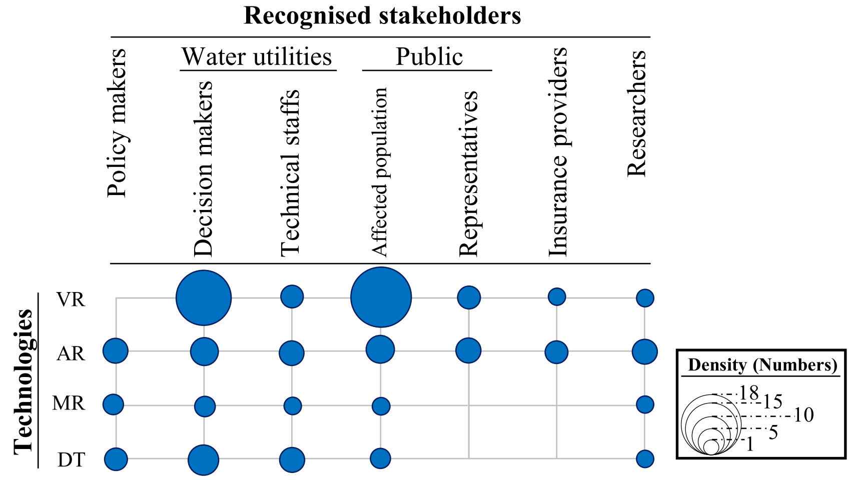

Fig. 4. Bubble plot illustrating the distribution of stakeholders' engagement based on various cutting-edge technologies in flood visualisation studies.

the engagement of technical staff as crucial stakeholders as they can ensure that the technical components of flood visualisation tools are accurate, reliable, and robust, providing a solid foundation for decision-making processes (Zhang et al., 2020).

Fig. 4 also emphasises that the significant number of VR studies engaging the affected population may be attributed to the user-friendly nature of VR platforms and devices have become more accessible and affordable in recent years, making it easier to involve a larger number of participants (Burian et al., 2020). Additionally, the immersive nature of VR can create a stronger emotional connection and sense of presence, allowing individuals to better internalise the potential consequences of flooding. Conversely, while several articles focused on representatives utilising VR and AR, there exists a lack of research encompassing MR and DT technologies. The inclusion of representatives using VR and AR demonstrates an increasing recognition of their potential in involving this group and establishing a platform for collaborative decision-making and fostering meaningful discussions (Su et al., 2021). However, the absence of research in the realm of MR and DT can be attributed to limited accessibility, technical complexities, or insufficient awareness pertaining to the potential advantages of these technologies (White et al., 2021).

Similar to representatives, a number of studies have addressed the involvement of insurances using VR and AR technologies. However, there is a lack of research exploring the engagement this group through MR and DT technologies. VR and AR offer interactive experiences that can aid in risk assessment, claim adjustment, and communication of flood information. By leveraging the interactive nature of them, insurances can enhance their risk modelling capabilities and improve underwriting accuracy (Tomkins and Lange, 2019). The absence of studies in the field of MR and DT area may be attributed to pressing research priorities, limited resources, or a lack of recognition of the specific requirements of this group in the flood risk management context. Researchers have been also involved in several studies across all cutting-edge technologies. It is concluded that while these studies have recognised the valuable contribution of researchers in advancing visualisation technologies, there remains room for further exploration as the involvement of researchers brings a wealth of expertise and knowledge in areas such as visualisation techniques and human–computer interaction. Their participation ensures scientific exploration and critical evaluation of the effectiveness and limitations of these technologies (Li *et al.*, 2015).

5.2. Contribution analysis of recognised stakeholders across flood visualisation objectives

Table 4 provides an insightful overview of the primary flood visualisation objectives. These objectives encompass critical areas such as flood damage assessment, which aims to evaluate the extent and impact of flood-related destruction. Flood inundation simulation focuses on accurately modelling and visualising the spatial extent and progression of flooding. Lastly, flood evacuation routing is explored, emphasising the development of efficient and effective evacuation plans for vulnerable areas during flood events.

Table 4
Primary flood visualisation objectives discussed in flood visualisation studies.

Flood visualisation objective	Description	Reference
Flood damage assessment	Quantifying and evaluating the magnitude of human or property damage inflicted by flood events which necessitates the comprehensive analysis of various factors such as property damage, disruption to critical infrastructure, economic losses, and potential environmental ramifications.	Mol et al. (2022)
Flood inundation simulation	Accurate modelling and simulation of the of flood inundation which entails the integration of advanced computational models, geospatial data, and cutting-edge visualisation techniques	Su et al. (2021)
Flood evacuation routing	Optimising evacuation strategies during flood events considering crucial variables such as population distribution, transportation networks, flood forecast information, and time constraints inherent to evacuation processes.	Li *et al.* (2022a)

Regarding these objectives, Fig. 5 shows a stream-flow diagram that examines the involvement of stakeholders in research works focused on the discussed visualisation objectives. Overall, Fig. 5 demonstrates that flood inundation simulation has garnered significant attention as a primary objective in flood visualisation. Moreover, when it comes to flood visualisation, the public and water utility groups have made greater contributions compared to other stakeholders. Regarding flood damage visualisation, VR is the primary method employed, while MR is not commonly utilised for this purpose. However, all technologies are employed for the other two objectives.

Studies utilising AR reveals a predominant focus on flood inundation simulation (Puertas *et al.*, 2020; Zhang et al., 2020). Alternatively, several numbers of studies explored the application of AR for flood evacuation routing, seeking to optimise evacuation strategies and routes during flood events (Mirauda et al., 2018). However, there is few research articles specifically addressing flood damage assessment using AR. These studies, which aim to evaluate the extent of damage caused by

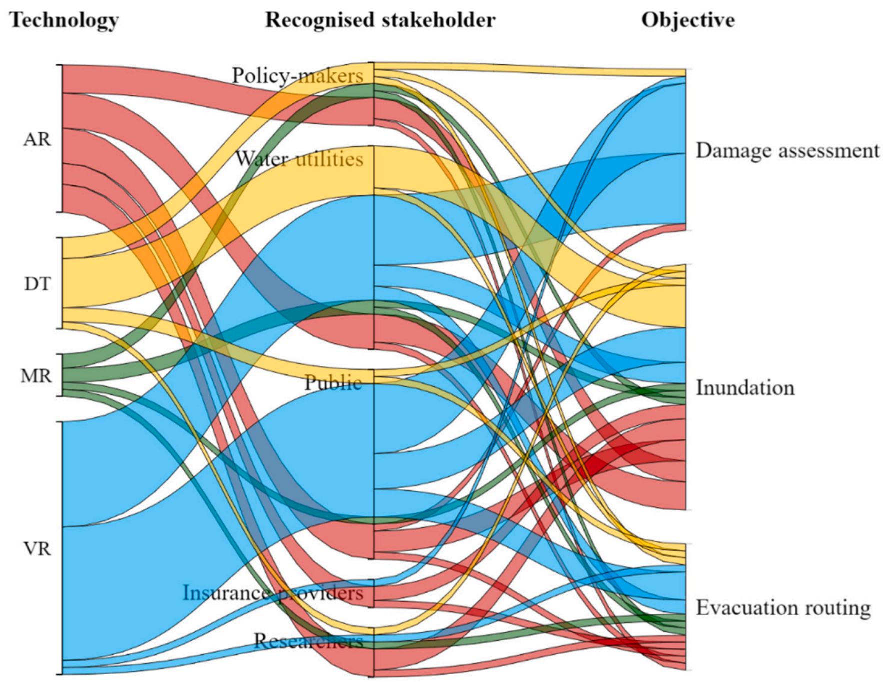

Fig. 5. Stream-flow diagram demonstrating the application of cutting-edge visualisation technologies in engaging stakeholders for varied flood visualisation objectives.

floods, involve the public group as the primary stakeholders. The involvement of stakeholders in inundation simulation and evacuation routing studies encompasses all recognised stakeholders (Tomkins and Lange, 2019). The limited representation of stakeholders in flood damage assessment studies may be attributed to the complexity of damage assessment processes, data availability challenges, or a lack of awareness regarding the potential applications of AR in this specific domain. Further research is needed to explore the potential of AR in facilitating comprehensive flood damage assessment that involve various stakeholder groups.

Research works used DT technology have demonstrated a primary focus on flood inundation simulation (Wang, Chen, & Wang, 2022; Ghaith et al., 2022). These studies leverage the capabilities of DT to accurately simulate the process of flood inundation, allowing for a detailed visualisation of flood scenarios. The involvement of water utilities in inundation simulation studies using DT indicates the recognition of their expertise in data analysis and flood risk management (Pedersen et al., 2021; Pedersen et al., 2022). However, few research articles specifically address flood damage assessment using DT. These studies have primarily involved policy-makers as the key stakeholders since their engagement in damage assessment studies allows for the integration of assessment results into policy development and decision-making processes (Truu et al., 2021; White et al., 2021). Nevertheless, further research is needed to explore the potential contributions and involvement of a wider range of stakeholders in flood damage assessment using DT.

MR studies have concentrated on inundation simulation and evacuation routing, with no specific focus on damage assessment (Li *et al.*, 2015). Despite the limited number of MR studies, they have successfully engaged diverse groups of stakeholders as they aim to use interactive capabilities of MR to enhance the understanding of flood progress. While the absence of MR studies focusing on damage assessment may be attributed to technical limitations or resource constraints, it highlights a potential area for future exploration in flood visualisation area. Furthermore, selected studies utilising VR have placed significant emphasis on damage assessment, which is driven by several factors (Wu et al., 2019). Firstly, assessing the extent of flood damage is essential for planning, resource allocation, and decision-making in risk management. Researchers can analyse the physical and economic impacts of flooding and provide valuable insights for control efforts. Besides, immersive nature of VR allows for a more comprehensive understanding of flood damage. Users can navigate and explore virtual environments and visualise the actual impact of floods on infrastructure (Simpson et al., 2022).

Alternatively, while VR studies strived to engage a wide range of stakeholders, public and water utilities have received great attention. Recognising the importance of community engagement and participatory approaches, researchers have sought to involve the public in the visualisation objectives (Aahlaad et al., 2021). This engagement allows for greater awareness and promoting community resilience. Involving water utilities in VR-based simulations enables them to assess the effectiveness of their response plans, testing and refining evacuation routes, and evaluating the resilience of critical facilities, and identifying potential vulnerabilities (Fu et al., 2021). It is worth noting that continued collaboration and engagement of various stakeholders in VR-based flood visualisation studies will contribute to the development of more robust and comprehensive flood risk management strategies for visualisation objectives.

6. Flood-risk based role mapping

The primary goal of this section is to map the role of recognised stakeholders in studies employing cutting-edge technologies for flood risk management stages. Accordingly, five key stages for flood risk management are identified including (1) prevention, i.e. reducing the likelihood and severity of flooding; (2) mitigation, i.e. improving the response capabilities; (3) preparedness i.e., reducing risks and potential impacts of flooding; (4) response, i.e. offering immediate assistance, and (5) recovery, i.e. rebuilding, rehabilitating, and restoring affected areas (Rouhanizadeh et al., 2020; Oubennaceur et al., 2021). Fig. 6 illustrates the distribution of focus among various stakeholders, categorised according to the risk management stages. Overall, the findings indicate that these studies have engaged stakeholders from all groups during the mitigation, preparedness, and response stages. However, representatives and insurance providers were not considered in the prevention stages, while policy-makers and researchers were not prominently

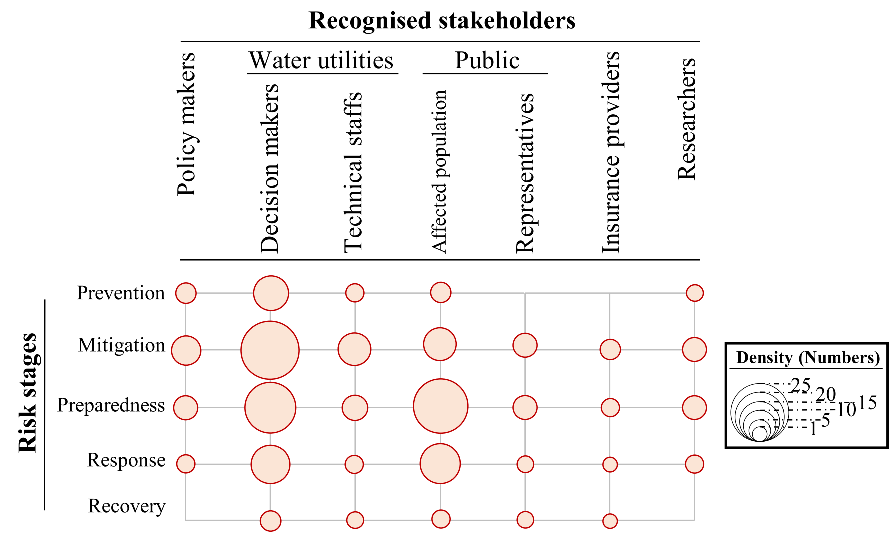

Fig. 6. Bubble plot illustrating the distribution of stakeholders' engagement based on flood risk management stages in flood visualisation studies.

involved in the recovery stage. Additionally, these studies have primarily concentrated on engaging decision-makers and the affected population, particularly during the stages of mitigation, preparedness, and response.

6.1. Policy makers

Several research works focused on the involvement of policy-makers in all stages of flood risk management, namely prevention, mitigation, preparedness, and response. They recognised the significance of engaging policy-makers as stakeholders in shaping and implementing effective strategies to address flood risks in the mentioned stakeholders (Rydvanskiy and Hedley, 2021). However, a notable gap exists in the literature concerning the involvement of policy-makers in the recovery stage. This stage, which focuses on post-flood restoration, reconstruction, and long-term resilience building, is a critical phase that requires active engagement and policy interventions. (Luo et al., 2021). This gap suggests the need for further exploration and investigation into the role of policy-makers in the recovery stage, as their involvement can play a crucial role in guiding recovery efforts and allocation of resources.

6.2. Water utilities

There are a relatively higher number of studies focusing on the mitigation and preparedness stages (Aahlaad et al., 2021). Emphasis on the mitigation stage aligns with the overarching objective of reducing the exposure and vulnerability of communities to flood hazard, as recognised by decision-makers. The emphasis on preparedness underscores the understanding that proactive planning and preparedness measures can effectively mitigate the impacts of flooding and facilitate more efficient response efforts. Similarly, the involvement of technical staff is evident across all risk management stages, with a particular emphasis on mitigation (Bartos and Kerkez, 2021). This emphasis can be attributed to the recognition of technical staff's expertise in assessing vulnerabilities, analysing flood hazards, and designing and implementing mitigation measures. Their contributions in utilising cutting-edge technologies for flood risk assessment and evaluating the efficacy of mitigation strategies are pivotal in ensuring comprehensive flood risk management practices (Macchione et al., 2019).

6.3. Public

Selected research works exhibited a notable commitment to involving the affected population across all stages of flood risk management. Notably, there is a significant emphasis on the preparedness stage, and relatively high focus on the mitigation and response stages (Sermet and Demir, 2019). The emphasis on the preparedness stage signifies the recognition of the affected population as active participants in building resilience, fostering community-driven responses, developing emergency response plans, and adopting appropriate measures to mitigate the impacts of flooding. By involving the affected population in the mitigation stage, these studies seek to ensure that community perspectives, needs, and concerns are considered in the development and implementation of effective mitigation strategies. Furthermore, the emphasis on the response stage highlights the efforts made by studies to understand the experiences, perceptions, and challenges faced by the affected population to develop of more effective response strategies (Fujimi and Fujimura, 2020).

A notable gap exists in the literature concerning the engagement of representatives in the prevention stage. Several factors may contribute to this, including a predominant focus on immediate response efforts following flood events, which may divert attention from long-term planning and preventive measures. Furthermore, challenges related to stakeholder coordination, limited resources, and institutional barriers may hinder the inclusion of representative boards in prevention-focused studies (Mirauda et al., 2018).

6.4. Insurance providers

The involvement of insurance providers in visualisation studies has primarily been observed in all stages, while the prevention stage has remained unaddressed (Zhang et al., 2020). The absence of studies focusing on prevention can be attributed to several factors. Firstly, the prevention stage often entails long-term planning, regulatory measures, and strategic interventions, which may lead insurance to perceive their involvement in this stage as less immediate. Secondly, the prevention stage's complexity and interdisciplinary nature may pose challenges in terms of stakeholder coordination and collaboration, necessitating greater effort and resources to effectively engage insurances (Zhu et al., 2014).

6.5. Researchers

Lastly, researchers have been prominently involved across all stages of flood risk management, except for the recovery stage (Ghaith et al., 2022). The scarcity of studies focusing on the recovery stage stems from its nature, which predominantly involves post-flood assessments, rehabilitation, and reconstruction efforts aimed at restoring affected areas and communities. While researchers can offer valuable insights and expertise in areas such as modelling and impact assessment, their involvement in the recovery stage may be perceived as less immediate. Moreover, the recovery stage necessitates rapid response and decision-making, with a heightened emphasis on practical actions that may lie outside the academic sphere of influence.

7. Impact of the recognised stakeholders on cutting-edge visualisation technologies

The primary focus of recent flood visualisation studies lies in engaging stakeholders in the flood risk management and understanding the impacts of digital visualisation on them, rather than specifically assessing how these stakeholders can contribute to the advancement and improvement of these techniques. This section aims to shed light on the potential impacts that the recognised stakeholders can have on enhancing the CEVT performance and promoting their widespread use.

Table 5 presents valuable insights regarding these impacts. Water utilities can play a pivotal role in improving the performance of visualisation technologies and driving their adoption. Their expertise and data contributions are essential in enhancing the accuracy and reliability of these technologies. By providing domain-specific knowledge, water utilities enable the testing and validation of visualisation models, ensuring their efficacy in real-world applications (Antonios et al., 2023). Similarly, the active involvement of public contributes to the enhancement and promotion of flood visualisation technologies (Auliagisni et al., 2022). Their involvement enriches the accuracy, relevance, and usability of these technologies through contributing data, local knowledge, feedback, and user experience. Moreover, their engagement fosters community empowerment, awareness, and collaborative governance, leading to more effective flood risk management practices.

As outlined in Table 5, policy-makers enhance the adoption and effectiveness of flood visualisation technologies by integrating them into policies and regulations, providing funding and support, and promoting data accessibility and sharing which ultimately leads to increased resilience to floods (Vanderhorst et al., 2021). Researchers can also improve cutting-edge technologies by developing innovative algorithms and models, collaborating with stakeholders, providing expertise in data interpretation, engaging social media feeds, and disseminating research findings to promote their adoption in flood risk management (Ye et al., 2023). Insurance providers can improve the performance of visualisation technologies and promote their use by sharing valuable data, collaborating with technology developers, and integrating the tools into risk management practices. Their contribution includes providing insights on flood risks and damages, addressing gaps in current methods, and raising awareness among clients about the benefits of these technologies for risk assessment and claims management (Kanbara and Shaw, 2022).

8. Potential engagement and future perspective

This section delves into the identifying of neglected stakeholders in flood visualisation studies, employing the framework presented in Section 4. The research aims to shed light on these often-overlooked stakeholders and emphasises their significant impacts on the development and utilisation of cutting-edge technologies. By elucidating their roles and exploring the mutual impacts between stakeholders and technologies, this study paves the way for further investigations in this field, thereby enabling more effective flood risk management strategies and fostering the adoption of cutting-edge technologies.

8.1. Analysis of overlooked authorities

Table 6 presents an overview of potential but neglected authorities' stakeholders in cutting-edge flood visualisation studies, majorly environmental agencies, local councils, and meteorological organisations.

Table 5
Potential impacts of recognised stakeholders in recent studies on cutting-edge technologies.*

Stakeholder	Impact of stakeholders on technology
Water utilities	
Decision-makers	- Defining the geographical boundaries and parameters of flood visualisation in area of interest - Ensuring comprehensiveness and accuracy of data utilised in flood visualisations - Choosing appropriate flood visualisation models that meet specific criteria such as computational efficiency, ease of use, and affordable costs to facilitate communication and interpretation of flood-related data
Technical staff	- Collecting pertinent data on flood risk parameters impacting on the quality of visualisations - Conducting calibration procedures for flood visualisation models - Offering feedback to model developers by testing model outputs with their experiences - Assessing the accuracy of tools in real case flood events
Public	
Affected population	- Offering insights on flood visualisation tools and their user-centred design - Participating in testing and evaluation of tools, providing feedback and areas of improvement - Enhancing the utilisation and adoption of tools by advocating for community engagement
Representatives	- Facilitating the development of user-friendly platforms - Collaborating with experts in visual communication and engagement - Aiding on identifying effective strategies for reaching diverse audiences
Policy-makers	- Providing financial support for the tools advancement aimed at enhancing flood-related data representation and communication - Offering regulation and cloud-based data storage to facilitate data availability - Deciding on appropriate strategies for presenting flood risk information and identifying the intended audience of the visualisations
Researchers	- Integrating cutting-edge data analytics techniques and artificial intelligence to analyse large amounts of flood data and create improved flood visualisation tools. - Creating more interactive and immersive visualisations enabling users to explore the impact of various flood scenarios. - Employing geospatial data and mapping technologies to produce comprehensive flood visualisations displaying the location, extent, and intensity of flooding. - Enhancing visualisation tools by integrating data from social media feeds to generate a more comprehensive and accurate representation of the flood situation
Insurance providers	- Augmenting visualisation methods by conducting distinctive flood risk assessments and visualisations to offer supplementary data and perspectives. - Disseminating data and information to foster more thorough and precise flood visualisations. - Allocating resources to research and develop advanced flood risk models and partnering with academic institutions to incorporate state-of-the-art scientific modelling techniques

*: Inspired by Vanderhorst et al. (2021); Auliagisni et al. (2022); Kanbara and Shaw (2022); Antonios et al. (2023); Ye et al. (2023).

Environmental agencies are responsible for monitoring the environmental impacts of floods in urban areas, including assessing water quality, ecological systems, and habitats affected by floods, as well as working towards their preservation and restoration (Fujimi *et al.,* 2020). They also develop and implement measures to mitigate the environmental damages caused by urban floods and actively promote environmental awareness and public education regarding the importance of sustainable practices in reducing flood risks.

By involving these stakeholders in the development, application, and promotion of CEVT, their performance can be significantly enhanced, ensuring alignment with environmental goals and facilitating their

Table 6
Mutual impacts of overlooked authorities' stakeholders in recent studies on cutting-edge technologies.*

Stakeholder	Impact of stakeholders on technology	Impact of technology on stakeholders
Environmental agencies	- Improving the simulations by integrating authoritative data into the tools - Establishing realistic flood scenarios derived from historical events to enhance the comprehension of ecological and environmental impacts - Incorporating environmental indicators, such as water quality, into tools to foster awareness and understanding of the significance of environmental considerations in flood risk management - Conducting training workshops aimed at introducing the potential of flood visualisation technologies and promoting their adoption.	- Facilitating access for agencies to real-time data from various sources, such as environmental sensors, satellite imagery, and weather forecasts - Enhancing the understanding of potential environmental impacts caused by floods through the creation of virtual replicas of real-world environments, allowing for the visualisation of vulnerabilities and risks associated with flooding - Providing a collaborative platform that facilitates the sharing of information, data, and insights among stakeholders, promoting interactive discussions and enabling the visualisation of different flood scenarios
Local councils	- Collaborating in research projects to provide feedback on technology development and incorporate the visualisation outputs into urban planning processes - Communicating flood risks to the public through incorporating the technologies into community outreach and education programs - Incorporating technologies into infrastructure development projects to improve their design, functionality, and resiliency - Investing in building the capacity of staff members to effectively utilise cutting-edge technologies to enhance their understanding and proficiency in using these technologies for decision-making and communication purposes	- Providing local councils with a deeper comprehension of the severity and extent of flood risks and their potential impacts on communities - Facilitating effective communication of complex flood-related information such as potential risks, protective measures, and emergency response strategies through interactive visualisations - Enhancing information sharing by utilising user-friendly interfaces, interactive maps, and virtual environments - Empowering local councils to make evidence-based decisions in flood risk management through data integration and analysis
Meteorological organisation	- Ensuring the tools reliability and effectiveness by providing meteorological organisations with essential information such as rainfall patterns, storm forecasts, and hydrological data - Enhancing the accuracy and realism of flood simulations and real-time visualisations by integrating real-time forecasting data from meteorological organisations into the tools, enabling more precise and up-to-date representations of potential flood scenarios	- Facilitating immersive and interactive visualisation of complex weather and flood data, allowing meteorological organisations to explore and analyse data in 3D environments - Enhancing communication of potential flood impacts to the public through the creation of engaging and informative visualisations - Supporting the development of early warning systems by integrating real-time visualisation capabilities with forecasting systems - Providing visual flood scenarios enabling to make informed decisions about resource allocation, emergency response, and flood mitigation - Providing impetus to analyse the flood risk data and provide inputs to the risk mitigation design

*Inspired by Zhu et al. (2014); PMI (2017); Seebauer et al. (2019); Fujimi *et al.* (2020); Gandini et al. (2020); White et al. (2021).

integration into effective flood risk management practices (White et al., 2021). Furthermore, CEVT offer powerful tools to raise awareness among environmental agencies and promote their engagement in flood risk management. These technologies facilitate real-time data integration and impact assessment, empowering agencies to make informed decisions and enhance environmental protection efforts (Seebauer et al., 2019).

Local councils, also known as municipalities or local authorities/ government bodies, have direct responsibilities in urban flood risk management. They are responsible for urban planning, infrastructure management, and emergency response within their jurisdictions. They oversee the maintenance and management of urban drainage systems, storm water management, and flood control infrastructure and during flood events, local councils coordinate emergency response efforts (Jun et al., 2013). Local councils can engage in collaborative partnerships with technology developers, enhance public awareness through targeted campaigns, formulate effective policies, and invest in staff capacity building initiatives.

Concurrently, the integration of these technologies into local council practices can raise awareness among stakeholders, improve communication channels, facilitate data-driven decision-making processes, and foster active engagement in flood risk management endeavours (Devagiri et al., 2022). Meteorological organisations provide critical weather forecasting and monitoring services that support urban flood risk management. They collect and analyse meteorological data to issue timely and accurate weather forecasts, including information about heavy rainfall events and potential flooding.

By providing early warnings and flood alerts to local councils, emergency management agencies, and the public, they help facilitate preparedness and response efforts (Gandini et al., 2020). Meteorological organisations' expertise in data collection, forecasting, risk assessment, and collaboration contributes to the accuracy, reliability, and effectiveness of these technologies in supporting flood risk management efforts (Lima et al., 2017). These technologies contribute to the advancement of meteorological practices and enhance the effectiveness of meteorological organisations in managing and mitigating the impacts of floods by enhancing their data analysis capabilities, improving forecasting and warning systems, and supporting decision-making processes (Costa et al., 2022).

8.2. Analysis of overlooked businesses

Another major overlooked group are businesses, as listed in Table 7, including contractors, suppliers, equipment manufactures, and software developers. Contractors play a vital role in flood risk management by providing expertise in engineering, construction, maintenance, and emergency response. They design and build flood protection infrastructure and maintain and repair existing structures (Zhu et al., 2022). They also install and maintain flood warning systems and assist with emergency response efforts to mitigate flood risks and promote community resilience. Contractors can leverage cutting-edge technologies to enhance design, streamline construction and maintenance processes,

Table 7
Mutual impacts of overlooked businesses stakeholders in recent studies on cutting-edge technologies.*

Stakeholder	Impact of stakeholders on technology	Impact of technology on stakeholders
Contractors	- Helping in access to accredited data by installing proper equipment, calibration, maintenance, and operation - Assessing impacts of potential flood events on infrastructure - Promoting tools by creating realistic training simulations such as practicing emergency protocols for flood response teams to enhance their skills in a safe and controlled virtual environment - Developing virtual replicas of infrastructures by integrating real-time data from sensors to monitor performance, identify maintenance needs, and simulate flood scenarios for predictive analysis	- Aiding in construction and maintenance activities through providing real-time guidance and overlaying flood protection infrastructure designs, and ensuring accurate and efficient implementation - Mitigating the costly risk of errors or delays during construction by detecting potential weaknesses in advance
Suppliers	- Allocating resources to research and develop new tools - Accessing new business opportunities, expanding customer base, and potentially entering new market segments	- Improving stakeholder communication by utilising visual representations to convey the risk mitigation measures taken - Optimising the delivery of goods and services through efficient resource allocation, resulting in cost savings and enhanced outcomes - Encouraging innovation and exploring novel approaches to develop advanced technologies and solutions that more effectively tackle flooding-related challenges
Equipment manufacture	- Engaging in the design, production, and development of hardware components and computing equipment specifically tailored for the tools - Investing in research and development - Customising and optimising hardware components to cater to the specific requirements of visualising floods - Adhering to industry standards and implementing rigorous quality control measures	- Generating a growing market demand for specialised hardware components and devices, resulting in increased sales and business opportunities for equipment manufacturers - Fostering technological innovation within the equipment manufacturing industry - Engaging in industry partnerships and collaborations to drive standardisation efforts, develop best practices, and facilitate the exchange of knowledge and expertise
Software developers	- Integrating data from various sources, such as satellite imagery, GIS data, and real-time sensor feeds - Designing user interfaces and interaction mechanisms that are intuitive and user-friendly, enabling smooth navigation and interaction with the visualisation technologies - Enhancing the accuracy of the technologies by refining algorithms and models, resulting in lifelike experiences - Optimising the performance of the technologies by effectively handling large-scale datasets and complex simulations	- Embracing novel development paradigms and frameworks, which necessitate the adoption of diverse programming languages, tools, and libraries specifically designed for the creation of immersive and interactive experiences - Keeping abreast of the latest advancements and technological breakthroughs in the field of visualisation technologies, enabling software developers to harness new capabilities and continually enhance their applications

* Inspired by Jun et al. (2013); PMI (2017); Costa et al. (2022); Wang et al. (2019); Wang et al. (2023).

optimise training, and ensure safety for better flood risk management (Wang et al., 2023). On the other hand, these technologies have a transformative impact on contractors, empowering them with enhanced operation capabilities, improved stakeholder engagement, and efficient decision-making.

Suppliers are responsible for the procurement and distribution of various products and materials necessary for flood risk management (Li et al, 2023). Their role is primarily focused on the supply chain and ensuring that the required equipment and materials are available when needed. Their role extends to collaboration with technology developers, integration into existing systems, training, and ensuring market accessibility to advance the adoption and utilisation of cutting-edge technologies (Wang et al., 2019). Alternatively, by embracing these technologies, suppliers can enhance their competitiveness, meet customer expectations, increase efficiency and productivity, access to new market opportunities, and drive growth in the flood risk management industry (Jun et al., 2013).

Besides, equipment manufacturers produce a wide range of flood management equipment, including flood barriers, pumps, sensors, monitoring devices, early warning and communication systems (Li *et al.,* 2022b). They ensure the availability of reliable and efficient equipment necessary for mitigating flood risks. These stakeholders have a significant impact on promoting cutting-edge technologies by driving technological advancements, providing essential hardware components, ensuring quality and standards compliance, and offering training and support. Alternatively, cutting-edge technologies create market demand, drive technological innovation, necessitate customisation and integration efforts, and stimulate research and development. These impacts shape the direction of equipment manufacturers, enabling them to meet the evolving needs of visualisation technologies and contribute to their advancement.

Software developers play a vital role in flood risk management by creating specialised software solutions for flood modelling, data analysis, and visualisation (Zhang et al., 2023). They integrate real-time data and sensors, design decision support systems, and ensure the continuous improvement of software applications. As illustrated in Table 7, their expertise in designing, developing, integrating data, creating user interfaces, enhancing realism, and collaborating with domain experts contributes to the effectiveness and utility of these technologies in flood risk management process (Chittaro et al., 2017). Cutting-edge technologies also have a significant impact on software developers, requiring them to acquire specialised skills, adopt new development paradigms, collaborate with domain experts, and keep pace with technological advancements.

8.3. Influential parameters on implementing cutting-edge flood visualisation technologies

Recognising the distinctions in stakeholder involvement and technology adoption between developed and developing countries is essential for formulating inclusive and targeted strategies to enhance flood visualisation worldwide. Primary key stakeholders involved in this context, including policy-makers, CEVT developers, and CEVT users play pivotal roles in shaping the implementation and success of flood visualisation technologies in their respective countries. Overall, developed countries tend to have more advanced technological infrastructures and greater financial resources, which allow them to access and deploy cutting-edge technologies. In contrast, developing countries may face challenges in acquiring such technologies due to financial constraints and limited technological advancements.

In developed countries, policy-makers may exhibit higher levels of awareness and understanding of the potential benefits of these technologies in flood management. Moreover, they often have more substantial financial resources to invest in cutting-edge solutions. In contrast, in addition to a lower level of awareness among policy-makers in developing countries regarding the potential of digital technologies in flood visualisation, financial limitations could also hinder their ability to invest in and promote the adoption of advanced solutions.

In developed countries, CEVT developers may consist of multinational and international corporations with extensive experience in the field and access to sophisticated technologies. Their establish networks and expertise which enable them to deliver complex and large-scale flood visualisation projects. In developing countries, CEVT developers primarily comprises local companies and small to medium-sized enterprises (SMEs). These entities might have limited access to cutting-edge technologies and possess less experience in executing large-scale flood visualisation projects due to resource constraints.

The users of flood visualisation technologies, such as emergency responders, operators, and local communities, also exhibit differences between developed and developing countries. In developed countries, users are likely to have a higher level of acceptance and awareness of technology, as they are accustomed to advanced technological solutions in various sectors. On the other hand, users in developing countries might have a lower level of acceptance and awareness of digital technologies, partly due to limited exposure to such innovations. The cultural, educational, and economic factors may influence their readiness to adopt and utilise cutting-edge flood visualisation tools.

9. Conclusions

This study undertook a comprehensive examination of stakeholder analysis concerning the implementation of CEVT i.e., VR, AR, MR, and DT in different urban flood risk management, including prevention, mitigation, preparation, response, and recovery. Stakeholders recognised in these studies entail water utilities, policy-makers, researchers, public, and insurance providers. Furthermore, the study addressed a notable gap in existing research by identifying and evaluating overlooked stakeholders who have not been adequately studied. The following are the key findings derived from this study:

- Water utilities, specifically decision-makers and technical staff, have been the primary focus of previous investigations. The public, comprising representative boards and affected populations, emerges as the second most prioritised group among these studies. However, there is a gap in research pertaining to comprehensively considering policy-makers, researchers, and insurance providers, indicating a wide scope for future studies.
- Stakeholders have been involved majorly in inundation simulation and evacuation routing. However, it is worth noting that damage assessment studies have predominantly focused on the involvement of the public, water utilities, and policy-makers.
- The applications of VR in engaging policy-makers, as well as the utilisation of MR and DT in engaging representatives and insurance providers are not explored fully.
- Although the engagement of recognised stakeholders in the mitigation, preparedness, and response stages of flood risk management has been extensively investigated, the involvement of representatives and insurance providers in the prevention stage is little studied.
- The role of policy-makers and researchers in the recovery stage has received limited attention. Their involvement can significantly influence preventive measures and guide recovery efforts.
- There has been limited exploration of how stakeholders can actively contribute to the advancement and improvement of these visualisation tools.

The findings of this study emphasise the importance of efficient communication and collaboration among stakeholders to achieve shared objectives. Effective communication channels and collaborative processes are crucial for addressing the complexities of urban flood risk management and ensuring that all stakeholders are actively involved and aligned in their goals. This study identifies overlooked stakeholders and suggests future research directions and serves as an overview, shedding light on the potential contributions and roles that stakeholders can play in the development and enhancement of these tools. However, further studies are required to evaluate how cutting-edge digital technologies can truly affect or be impacted by these stakeholders.

CRediT authorship contribution statement

Vahid Bakhtiari: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Farzad Piadeh:** Methodology, Formal analysis, Visualization, Validation, Writing – review & editing. **Albert S. Chen:** Supervision, Writing – review & editing. **Kourosh Behzadian:** Supervision, Conceptualization, Validation, Writing – review & editing.

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.

Data availability

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

Acknowledgements

The authors wish to thank the editor-in-chief, the associate editor and the anonymous reviewers for making constructive comments which substantially improved the quality of the paper. Chen's involvement in the work was supported by the project WATERLINE: Transforming Advanced Water Skilling Through the Creation of a Network of Extended reality Water Emulative Centres, jointly funded by the European Horizon European Programme (HORIZON-WIDERA-2021-ACCESS-05 under grant agreement No 101071306) and the UK Research and Innovation (Ref:10042020).

Declaration of generative AI in scientific writing

During the preparation of this work the authors used ChatGPT to improve readability and language of the text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eswa.2023.121426.

References

Aahlaad, M., Mozumder, C., Tripathi, N., & Pal, I. (2021). An object-based image analysis of worldview-3 image for urban flood vulnerability assessment and dissemination through ESRI story maps. *Journal of the Indian Society of Remote Sensing, 49*(11), 2639–2654.

Allam, Z., Sharifi, A., Bibri, S., Jones, D., & Krogstie, J. (2022). The metaverse as a virtual form of smart cities: Opportunities and challenges for environmental, economic, and social sustainability in urban futures. *Smart Cities, 5*(3), 771–801.

Amirebrahimi, S., Rajabifard, A., Mendis, P., & Ngo, T. (2016). A BIM-GIS integration method in support of the assessment and 3D visualisation of flood damage to a building. *Journal of spatial science, 61*(2), 317–350.

Antonios, P., Konstantinos, K., & Christos, G. (2023). A systematic review on semantic interoperability in the IoE-enabled smart cities. *Internet of Things*, Article 100754.

Auliagisni, W., Wilkinson, S., & Elkharboutly, M. (2022). Using community-based flood maps to explain flood hazards in Northland. *New Zealand. Progress in Disaster Science, 14*, Article 100229.

Bakhtiari, V., Piadeh, F., Behzadian, K. (2023). Application of innovative digital technologies in urban flood risk management. *EGU General Assembly 2023*, Vienna, Austria [online] available at doi.org/10.5194/egusphere-egu23-4143 [Accessed 04/06/2023].

Bhaduri, R. (2019). Leveraging culture and leadership in crisis management. *European Journal of Training and Development, 43*(5/6), 554–569.

Burian, T., Gorin, S., Radevski, I., & Vozenilek, V. (2020). A novel way to present flood hazards using 3D-printing with transparent layers of return period isolines. *DIE ERDE–Journal of the Geographical Society of Berlin, 151*(1), 16–22.

Carneiro, J., Rossetti, R., Silva, D., Oliveira, E. (2018). BIM, GIS, IoT, and AR/VR integration for smart maintenance and management of road networks: a review. In *2018 IEEE international smart cities conference (ISC2)*, pp. 1-7.

Chittaro, L., Sioni, R., Crescentini, C., & Fabbro, F. (2017). Mortality salience in virtual reality experiences and its effects on users' attitudes towards risk. *International Journal of Human-Computer Studies, 101*, 10–22.

Costa, T., Meneguette, R., & Ueyama, J. (2022). Providing a greater precision of Situational Awareness of urban floods through Multimodal Fusion. *Expert Systems with Applications, 188*, Article 115923.

Devagiri, J., Paheding, S., Niyaz, Q., Yang, X., Smith, S. (2022). Augmented Reality and Artificial Intelligence in industry: Trends, tools, and future challenges. *Expert Systems with Applications*, p.118002.

Fu, L., Zhu, J., Li, W., Zhu, Q., Xu, B., Xie, Y., … You, J. (2021). Tunnel vision optimization method for VR flood scenes based on Gaussian blur. *International Journal of Digital Earth, 14*(7), 821–835.

Fujimi, T., & Fujimura, K. (2020). Testing public interventions for flash flood evacuation through environmental and social cues: The merit of virtual reality experiments. *International Journal of Disaster Risk Reduction, 50*, Article 101690.

Gamberini, L., Bettelli, A., Benvegnù, G., Orso, V., Spagnolli, A., & Ferri, M. (2021). Designing "Safer Water". A Virtual Reality Tool for the Safety and the Psychological Well-Being of Citizens Exposed to the Risk of Natural Disasters. *Frontiers in psychology, 12*, Article 674171.

Gandini, A., Garmendia, L., Prieto, I., Álvarez, I., & San-José, J. (2020). A holistic and multi-stakeholder methodology for vulnerability assessment of cities to flooding and extreme precipitation events. *Sustainable Cities and Society, 63*, Article 102437.

Geaves, L. H., & Penning-Rowsell, E. C. (2016). Flood risk management as a public or a private good, and the implications for stakeholder engagement. *Environmental Science & Policy, 55*, 281–291.

Ghaith, M., Yosri, A., & El-Dakhakhni, W. (2022). Synchronization-Enhanced Deep Learning Early Flood Risk Predictions: The Core of Data-Driven City Digital Twins for Climate Resilience Planning. *Water, 14*(22), 3619.

Haynes, P., & Lange, E. (2016). Mobile augmented reality for flood visualisation in urban riverside landscapes. *Journal of Digital Landscape Architecture, 1*, 254–262.

Haynes, P., Hehl-Lange, S., & Lange, E. (2018). Mobile augmented reality for flood visualisation. *Environmental Modelling & Software, 109*, 380–389.

Jacquinod, F., & Bonaccorsi, J. (2019). Studying Social Uses of 3D Geovisualisations: Lessons Learned from Action-Research Projects in the Field of Flood Mitigation Planning. *ISPRS International Journal of Geo-Information, 8*(2), 84.

Jun, K., Chung, E., Kim, Y., & Kim, Y. (2013). A fuzzy multi-criteria approach to flood risk vulnerability in South Korea by considering climate change impacts. *Expert Systems with Applications, 40*(4), 1003–1013.

Kanbara, S., & Shaw, R. (2022). Disaster risk reduction regime in Japan: An analysis in the perspective of open data, open governance. *Sustainability, 14*(1), 19.

Kundu, S., & Nawaz, M. (2019). Geospatial risk communication and visualisation of natural hazards using augmented reality constructs. In *GCEC 2017: Proceedings of the 1st Global Civil Engineering Conference* (pp. 641–651).

Langenheim, N., Sabri, S., Chen, Y., Kesmanis, A., Felson, A., Mueller, A., Rajabifard, A., Zhang, Y. (2022). Adapting a digital twin to enable real-time water sensitive urban design decision-making. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, archives-XLVIII-4-W4.

Li, F., Trappey, A., Lee, C., & Li, L. (2022). Immersive technology-enabled digital transformation in transportation fields: A literature overview. *Expert Systems with Applications, 202*, Article 117459.

Li, W., Zhu, J., Haunert, J., Fu, L., Zhu, Q., & Dehbi, Y. (2022). Three-dimensional virtual representation for the whole process of dam-break floods from a geospatial storytelling perspective. *International Journal of Digital Earth, 15*(1), 1637–1656.

Li, W., Zhu, J., Dang, P., Wu, J., Zhang, J., Fu, L., & Zhu, Q. (2023). Immersive virtual reality as a tool to improve bridge teaching communication. *Expert Systems with Applications, 217*, Article 119502.

Li, Y., Gong, J., Song, Y., Liu, Z., Ma, T., Liu, H., … Yu, Y. (2015). Design and key techniques of a collaborative virtual flood experiment that integrates cellular automata and dynamic observations. *Environmental Earth Sciences, 74*, 7059–7067.

Lima, J., Roberto, R., Simões, F., Almeida, M., Figueiredo, L., Teixeira, J., & Teichrieb, V. (2017). Markerless tracking system for augmented reality in the automotive industry. *Expert Systems with Applications, 82*, 100–114.

Luo, L., Zhu, J., Fu, L., Pirasteh, S., Li, W., Han, X., & Guo, Y. (2021). A suitability visualisation method for flood fusion 3D scene guided by disaster information. *International Journal of Image and Data Fusion, 12*(4), 301–318.

Macchione, F., Costabile, P., Costanzo, C., & De Santis, R. (2019). Moving to 3-D flood hazard maps for enhancing risk communication. *Environmental Modelling & Software, 111*, 510–522.

Masalegooyan, Z., Piadeh, F., & Behzadian, K. (2022). A comprehensive framework for risk probability assessment of landfill fire incidents using fuzzy fault tree analysis. *Process Safety and Environmental Protection, 163*, 679–693.

Mirauda, D., Erra, U., Agatiello, R., & Cerverizzo, M. (2018). Mobile augmented reality for flood events management. *Water Studies, 47*, 418–424.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Medicine, 6*(7), e1000097.

Mol, J., Botzen, W., & Appendices, J. (2022). After the virtual flood: Risk perceptions and flood preparedness after virtual reality risk communication. *Judgment and Decision Making, 17*(1), 189.

Oubennaceur, K., Chokmani, K., El Alem, A., & Gauthier, Y. (2021). Flood risk communication using arcgis storymaps. *Hydrology, 8*(4), 152.

Pedersen, A., Borup, M., Brink-Kjær, A., Christiansen, L., & Mikkelsen, P. (2021). Living and prototyping digital twins for urban water systems: Towards multi-purpose value creation using models and sensors. *Water, 13*(5), 592.

Pedersen, A., Pedersen, J., Borup, M., Brink-Kjær, A., Christiansen, L., & Mikkelsen, P. (2022). Using multi-event hydrologic and hydraulic signatures from water level sensors to diagnose locations of uncertainty in integrated urban drainage models used in living digital twins. *Water Science and Technology, 85*(6), 1981–1998.

Piadeh, F., Behzadian, K., & Alani, A. (2022a). A Critical Review of Real-Time Modelling of Flood Forecasting in Urban Drainage Systems. *Journal of Hydrology, 607*, Article 127476.

Piadeh, F., Behzadian, K., Alani, A. (2022b). Multi-Step Flood Forecasting in Urban Drainage Systems Using Time-series Data Mining Techniques. *Water Efficiency Conference*, West Indies, Trinidad and Tobago [Accessed 15/03/2023].

Piadeh, F., Ahmadi, M., & Behzadian, K. (2022). A Novel Planning Policy Framework for the Recognition of Responsible Stakeholders in the of Industrial Wastewater Reuse Projects. *Journal of Water Policy, 24*(9), 1541–1558.

Piadeh, F., Behzadian, K., Chen, A., Campos, L., & Kapelan, Z. (2023). Event-Based Decision Support Algorithm for Real-Time Flood Forecasting in Urban Drainage Systems Using Machine Learning Modelling. *Journal of Environmental Modelling and Software, 167*, Article 105772.

Project Management Institute (PMI). (2017). A guide to the project management body of knowledge. *6th edition., Pennsylvania: Project Management Institute*, pp. 410-480.

Qamar, S., Anwar, Z., & Afzal, M. (2023). A systematic threat analysis and defense strategies for the metaverse and extended reality systems. *Computers & Security*, Article 103127.

Rafiei-Sardooi, E., Azareh, A., Choubin, B., Mosavi, A., & Clague, J. (2021). Evaluating urban flood risk using hybrid method of TOPSIS and machine learning. *International Journal of Disaster Risk Reduction, 66*, Article 102614.

Rouhanizadeh, B., Kermanshachi, S., & Nipa, T. (2020). Exploratory analysis of barriers to effective post-disaster recovery. *International Journal of Disaster Risk Reduction, 50*, Article 101735.

Rydvanskiy, R., & Hedley, N. (2021). Mixed reality flood visualisations: Reflections on development and usability of current systems. *International Journal of Geo-Information, 10*(2), 82.

Sarmah, T., Das, S., Narendr, A., & Aithal, B. (2020). Assessing human vulnerability to urban flood hazard using the analytic hierarchy process and geographic information system. *International Journal of Disaster Risk Reduction, 50*, Article 101659.

Schröter, K., Lüdtke, S., Redweik, R., Meier, J., Bochow, M., Ross, L., … Kreibich, H. (2017). Flood loss estimation using 3D city models and remote sensing data. *Environmental Modelling & Software, 105*, 118–131.

Seebauer, S., Ortner, S., Babcicky, P., & Thaler, T. (2019). Bottom-up citizen initiatives as emergent actors in flood risk management: Mapping roles, relations and limitations. *Journal of flood risk management, 12*(3), e12468.

Sermet, Y., Demir, I. (2019). Flood action VR: a virtual reality framework for disaster awareness and emergency response training. *ACM SIGGRAPH 2019 Posters*, pp. 1-2.

Simpson, M., Padilla, L., Keller, K., & Klippel, A. (2022). Immersive storm surge flooding: Scale and risk perception in virtual reality. *Journal of Environmental Psychology, 80*, Article 101764.

Singh, H., & Garg, R. (2016). Web 3D GIS application for flood simulation and querying through open source technology. *Journal of the Indian Society of Remote Sensing, 44*(4), 485–494.

Su, W., Lin, Y., Huang, C., Yang, C., & Tsai, Y. (2021). 3D GIS Platform for Flood Wargame: A Case Study of New Taipei City, Taiwan. *Water, 13*(16), 2211.

Sun, C., Puig, V., & Cembrano, G. (2020). Real-time control of urban water cycle under cyber-physical systems framework. *Water, 12*(2), 406.

Tomkins, A., & Lange, E. (2019). Interactive landscape design and flood visualisation in augmented reality. *Multimodal Technologies and Interaction, 3*(2), 43.

Truu, M., Annus, I., Roosimägi, J., Kändler, N., Vassiljev, A., & Kaur, K. (2021). Integrated decision support system for pluvial flood-resilient spatial planning in urban areas. *Water, 13*(23), 3340.

Vanderhorst, H., Suresh, S., Renukappa, S., & Heesom, D. (2021). Strategic framework of Unmanned Aerial Systems integration in the disaster management public organisations of the Dominican Republic. *International Journal of Disaster Risk Reduction, 56*, Article 102088.

Wang, C., Hou, J., Miller, D., Brown, I., & Jiang, Y. (2019). Flood risk management in sponge cities: The role of integrated simulation and 3D visualisation. *International Journal of Disaster Risk Reduction, 39*, Article 101139.

Wang, Y., Chen, X., & Wang, L. (2022). Differential Semi-Quantitative Urban Risk Assessment of Storm Surge Inundation. *Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, 3*, 177–185.

Wang, H., Xu, S., Xu, H., Wu, Z., Wang, T., & Ma, C. (2023). Rapid prediction of urban flood based on disaster-breeding environment clustering and Bayesian optimized deep learning model in the coastal city. *Sustainable Cities and Society*, 104898.

White, G., Zink, A., Codecá, L., & Clarke, S. (2021). A digital twin smart city for citizen feedback. *Cities, 110*, Article 103064.

Wolf, K., Dawson, R., Mills, J., Blythe, P., & Morley, J. (2022). Towards a digital twin for supporting multi-agency incident management in a smart city. *Scientific reports, 12*(1), 16221.

Woolway, R., Kraemer, B., Lenters, J., Merchant, C., O'Reilly, C., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews Earth & Environment, 1*(8), 388–403.

Wu, Y., Peng, F., Peng, Y., Kong, X., Liang, H., & Li, Q. (2019). Dynamic 3D simulation of flood risk based on the integration of spatio-temporal GIS and hydrodynamic models. *ISPRS International Journal of Geo-Information, 8*(11), 520.

Ye, X., Du, J., Han, Y., Newman, G., Retchless, D., Zou, L., … Cai, Z. (2023). Developing human-centered urban digital twins for community infrastructure resilience: A research agenda. *Journal of Planning Literature, 38*(2), 187–199.

Zhang, G., Gong, J., Li, Y., Sun, J., Xu, B., Zhang, D., … Yin, B. (2020). An efficient flood dynamic visualisation approach based on 3D printing and augmented reality. *International Journal of Digital Earth, 13*(11), 1302–1320.

Zhang, X., Chen, L., Jiang, J., Ji, Y., Han, S., Zhu, T., … Tang, F. (2023). Risk analysis of people evacuation and its path optimization during tunnel fires using virtual reality experiments. *Tunnelling and Underground Space Technology, 137*, Article 105133.

Zhu, J., Yin, L., Wang, J., Zhang, H., Hu, Y., & Liu, Z. (2014). Dam-break flood routing simulation and scale effect analysis based on virtual geographic environment. *Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8*(1), 105–113.

Zhu, R., Aqlan, F., Zhao, R., & Yang, H. (2022). Sensor-based modeling of problem-solving in virtual reality manufacturing systems. *Expert Systems with Applications, 201*, Article 117220.