



A critical review for the application of cutting-edge digital visualisation technologies for effective urban flood risk management

Vahid Bakhtiari^a, Farzad Piadeh^{b,c}, Kourosh Behzadian^{b,d,*}, Zoran Kapelan^e

^a Civil and Environmental Engineering Department, Amirkabir University of Technology (AUT), 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 Department of Civil, Environmental and Geomatic Engineering, University College London, Gower St, London WC1E 6BT, UK

^e Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology (TU Delft), Delft, Netherlands

ARTICLE INFO

Keywords:

Augmented reality
Digital twin
Digital visualisation
Flood risk management
Systematic review
Virtual reality

ABSTRACT

Cutting-edge digital visualisation tools (CDVT) are playing an increasingly important role in improving urban flood risk management. However, there is a paucity of comprehensive research examining their role across all stages of urban flood risk management. To address, this study conducts an integrated critical review to identify the application of CDVT and assess their contribution to the prevention, mitigation, preparation, response, and recovery stages of flood risk management. The results show that virtual reality, augmented reality, and digital twin technologies are the primary CDVT used in urban flood visualisation, with virtual reality being the most frequently used. The focus of urban flood visualisation studies has been primarily on preparation and mitigation stages. However, there is a need to investigate the application of these technologies in the entire urban water cycle. Furthermore, there is potential for greater adoption of digital twin, especially in simulating urban flood inundation and flood evacuation routes. Integrating real-time data, data-driven modeling, and CDVT can significantly improve real-time flood forecasting. This benefits stakeholders and the public by enhancing early warning systems, preparedness, and flood resilience, leading to more effective flood risk management and reduced impacts on communities.

1. Introduction

Climate change has contributed to a surge in the frequency and intensity of extreme weather events such as heavy rainfall, hurricanes, and storm surges. Consequently, urban areas have become more susceptible to flooding, primarily due to factors such as high population density, impervious surfaces, and inadequate drainage systems (Piadeh et al., 2022). The rapid pace of urbanisation worldwide has resulted in more people to congregate in cities, leading to an increase in impervious surfaces such as roads, parking lots, and buildings. These surfaces hinder water infiltration, causing higher runoff and escalating the risk of flooding (Saurav et al., 2021). Furthermore, many urban regions have inadequate drainage systems, further exacerbating the risk of flooding. Even moderate rainfall can swiftly overwhelm these systems, leading to flooding and extensive damage to infrastructure and property (Huang et al., 2020). Additionally, the adverse effects of extreme weather events are disproportionately felt by vulnerable populations, such as those

living in low-lying areas or areas with inadequate infrastructure. These populations experience extensive consequences that impact sustainability aspects of the city, including its social fabric (such as livelihood loss and forced displacement), economic stability (such as loss of businesses and damage to infrastructure), and environmental well-being (such as natural resource depletion and pollution and contamination) (Martyr-Koller et al., 2021).

Urban flooding in this study considers any type of the temporary inundation or water overflow in urban areas due to various factors such as pluvial (flash or surface water), fluvial (riverine), coastal (high tides or tidal surges), groundwater, and sewer flooding mainly due to extreme weather or inadequate capacity of urban drainage systems (Hamil, 2011). When rainfall runoff exceeds the capacity of urban infrastructure, including storm drains, sewers, and canals, urban flooding occurs on streets, footpaths. Urban areas, with their high population density and extensive impervious surfaces such as roads and building roofs, are particularly vulnerable to this type of flooding ranging from minor

* Corresponding author at: School of Computing and Engineering, University of West London, St Mary's Rd, London W5 5RF, UK.

E-mail address: kourosh.behzadian@uwl.ac.uk (K. Behzadian).

<https://doi.org/10.1016/j.scs.2023.104958>

Received 30 April 2023; Received in revised form 24 July 2023; Accepted 22 September 2023

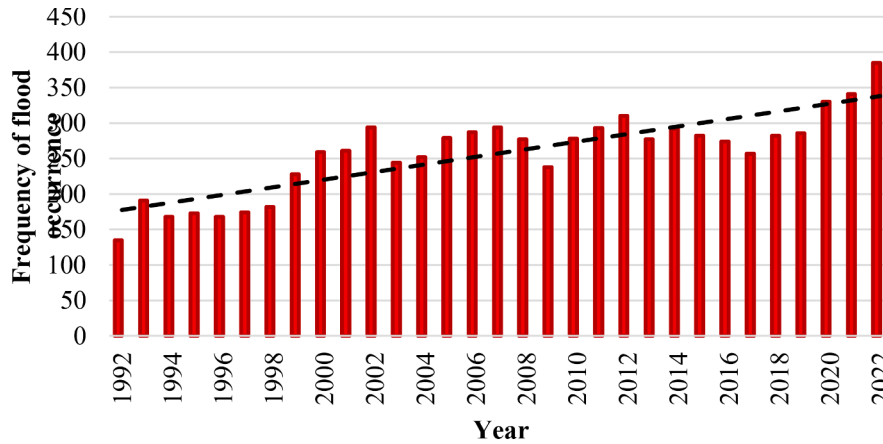
Available online 24 September 2023

2210-6707/© 2023 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

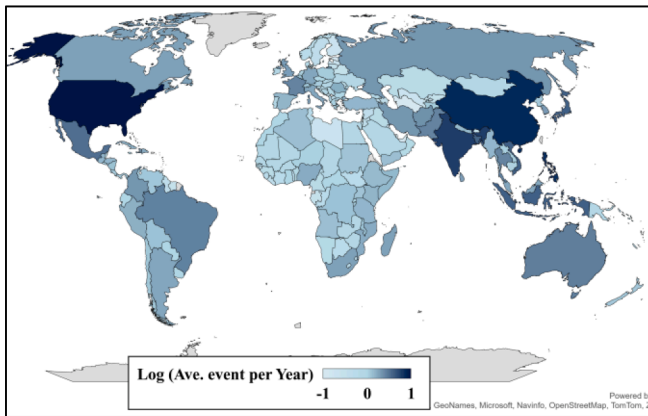
inconveniences to major disasters (Piadeh et al., 2022).

Fig. 1a shows the historic trend of frequency of flood occurrence over the past 30 years, which clearly shows a relatively annual increase mainly due to the climate change impacts. However, this frequency, severity of its consequences and resultant risks can be variable in various countries and regions of the world. For example, the annual average frequency of urban flood events in some countries such as the US, China and India are higher than the rest of the world (Fig. 1b). This rate is followed by countries in Southeastern Asia while this frequency is relatively low in Europe and Africa. On the other side, the average

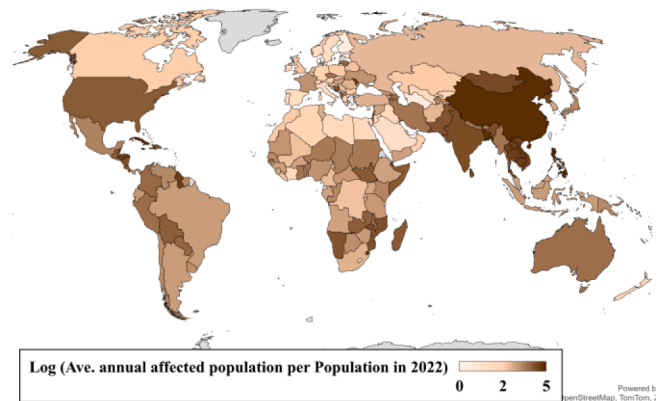
damage per event (Fig. 1d) is quite high in many regions/countries such as North America, Europe, China, India, Latin America and Australia. However, the high-risk countries for urban flood (annual average of damage cost per PPP in 2022) as shown in Fig. 1e are only China, India and US. Europe, Southeastern Asia, Australia and Latin America can be categorised as average risk followed by Africa which is quite low risk as both frequency and annual damage of flood events are relatively low in Africa. In addition, the average annual population affected by flood per country population in 2022 (Fig. 1b) is relatively high in the countries with the highest frequency of flood events such as US, China and India



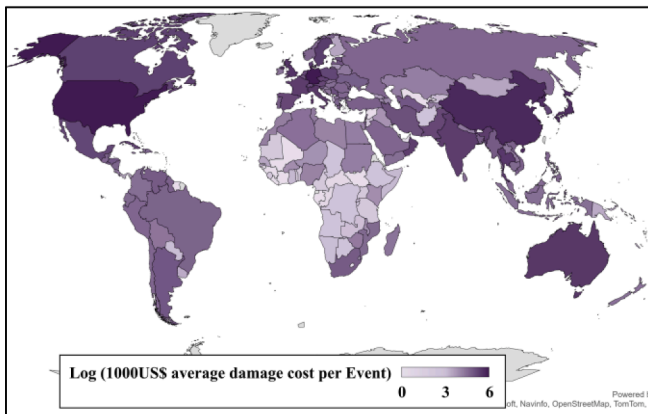
(a)



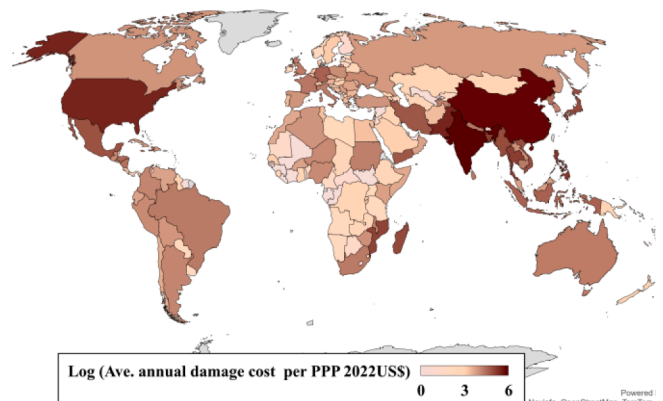
(b)



(c)



(d)



(e)

Fig. 1. Recorded urban flood events over the past 30 years: (a) historic trend of frequency of major flood events, (b) average annual flood occurrence, (c) average of annual affected population per population of country in 2022, (d) average damage cost estimated per event, and (e) average of annual damage cost per GDP PPP in 2022 (raw data collected from CRED (2022), all cost data are adjusted based on 2022, data are shown in logarithm form for better comparison)

followed by countries with low population such as those in sub-Saharan Africa.

Many sustainable structural and non-structural measures have been introduced in recent decades to mitigate urban flood risk among which, non-structural flood risk management plays a critical role in mitigating the destructive repercussions of such events (Mai et al., 2020). Non-structural flood risk management refers to a series of measures aimed at decreasing the vulnerability of individuals, assets, and infrastructure to flood events, without relying on physical structures (Ciullo et al., 2017). Accordingly, non-structural measures encompass a range of strategies, including land use planning, flood forecasting and early warning systems, emergency response planning, and public education and awareness campaigns (Shah et al., 2018). For example, flood forecasting and early warning systems can make use of any physical characteristics of the urban water infrastructure and data collected from various sources such as hydrology and weather to predict water levels in urban drainage infrastructure during floods and evaluates non-structural measures' effectiveness, thus providing valuable insights for flood impact mitigation decisions (Piadeh et al. 2022). Flood visualisation technologies are valuable tools that, when combined with either physically based or data driven modelling, can significantly provide insight into the potential impacts of flooding and the mitigation strategies required to alleviate their impacts (Da Silva et al., 2020).

Flood visualisation is the process of creating visual representations of flood events using various technologies. Since its inception, flood visualisation has evolved significantly from the traditional manual methods used to create flood maps by hand-drawing flood boundaries onto paper maps (Ma et al., 2020). With the introduction of geographic information systems (GIS), digital flood maps were developed, allowing flood data to be stored and analysed in a digital format. However, early digital maps were often two-dimensional and lacked the ability to provide detailed, immersive, and interactive experiences (Macchione et al., 2019). Although physically based and data-driven modelling have enabled flood data to be analysed in three dimensions (3D), it requires specialised expertise to use and is inaccessible to many communities and organisations (Towe et al., 2020). Even web-based flood mapping tools, which have made flood data more accessible to the public, still often present data in a two-dimensional format, despite offering a new level of transparency and interactivity (Carver, 2019). The CDVT in flood risk management has evolved significantly in recent years, incorporating advanced tools such as virtual reality (VR), augmented reality (AR), and digital twin (DT) into flood risk management (Guo et al., 2021; Puertas et al., 2020). These technologies have been instrumental in improving flood visualisation by facilitating a more engaging and intuitive approach. They enable involved stakeholders, such as decision-makers and the public, to utilise immersive simulations that showcase the potential impacts of floods leading to more effective flood management strategies (IWA, 2019).

VR allows users to immerse themselves in a computer-generated 3D environment and gain a better understanding of the potential impacts and consequences of flooding (Simpson et al., 2022). AR, on the other hand, overlays digital information onto the real world, allowing stakeholders to view the potential impacts of flooding in their real-world context. This can be particularly useful for decision-makers and emergency responders who need to quickly assess the potential risks and impacts of a flood event (Zhang et al., 2020). Finally, DT technology allows for the creation of a virtual replica of a real-world system or environment, such as a water infrastructures or buildings under load of flooding. DT can provide a detailed and accurate representation of urban drainage systems, allowing stakeholders to simulate and evaluate different flood management strategies in a virtual environment before implementing them in the real world (Ramu et al., 2022).

While these digital technologies has recently been applied to various applications including urban flooding to enhance flood risk management, there is no comprehensive review to critically analyse how these technologies have been used in various components of urban flood risk

management and identify the challenges and potentials in the current and further applications. Some recent review papers of using digital technologies civil engineering and built environment infrastructures are outlined here. For example, Zhu and Li (2021) provided an overview of the current state-of-the-art in using VR and AR technologies for emergency management in the built environment. While they discussed the application of the recently developed technologies in the pre-emergency preparation, emergency response, and post-emergency recovery phases, they overlooked their application for disaster management especially in urban flooding. Muthalif et al. (2022) highlighted the potential of AR visualisation for subsurface utilities, but further investigation is recommended to explore their application in flood management. Meanwhile, Lei et al. (2023) identified a range of challenges and advantages associated with the use of DT technologies in the context of smart cities. Other researchers also investigated the role of DT in achieving smart water governance, maintaining water infrastructures, and designing sustainable smart cities (Pesantez et al., 2022; Xia et al., 2022).

Despite the valuable efforts that have been made so far, there are still potential knowledge gaps which this study aims to address. The novelty of this study lies in its comprehensive overview of various technologies and their applications within the context of urban flood risk management. By providing insights into different developed platforms and their applications, this study provides a valuable contribution to the literature by examining the roles of these technologies throughout the entire risk management process. Additionally, the discussion of current challenges and identification of promising areas for future research further distinguishes this work in the field of urban flood risk management.

2. Review methodology

The scope of this study is specifically focused on urban flooding and excludes other types of flooding, such as non-urbanised river flooding, large reservoir breaking dams, lakes and wetland overflowing. However, relevant non-urban cases are also covered to capture recently developed concepts in the field used for knowledge gap identification or future directions.

As a research design framework shown in Table 1, the research

Table 1
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, recommended by Moher et al. (2009) | (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 (3D OR Digital) AND (Print OR Present OR Map OR GIS OR Street OR Flood) OR (Digital AND Twin) OR ((Online OR Interactive) AND (Simulation AND Platform) | 43 |
| S ₄ | Results were screened for finding risk management stages. Stages are identified inspired by Bhaduri (2019) | Prevention OR Mitigation OR Preparedness OR Response OR Recovery | 40 |

database was collected from the Scopus search engine using the recommended method of searching in titles, abstracts, and keywords as suggested by Moher et al. (2009). A set of four search/screening strategies (S₁-S₄) were applied to narrow down the search results. The search results began with 891 publications in the first stage (S₁), which were gradually narrowed down in stages S₂ and S₃ with 43 studies identified for applied digital visualisation of urban flooding (S₃). Finally, 40 studies were identified in the fourth stage (S₄) focusing on various stages of urban flood risk management.

2.1. Bibliometric analysis

The present study conducted a scientific examination of the selected publications, including a geographical distribution analysis and bibliometric analysis. Fig. 2a shows that the majority of relevant studies are from Europe and Asia, accounting for 39% and 37% of the total publications, respectively. The number of publications appears to be positively correlated with the level of economic development of the countries. The top four countries in terms of publication number are China, the USA, the UK, and Italy, all of which have some of the world's largest economies. This trend highlights the economic importance of the issue, especially considering the increasing urbanisation and challenges posed by climate change in the future.

Although flooding is a global phenomenon, as illustrated in Fig. 1, it appears that there is a need to further explore the potential of CDVT in African, Central and South American, Southeast Asian, and Oceania countries. It is important to note that the application of these technologies has been tested in only 18 countries so far based on selected research works. Thus, to truly assess their effectiveness on a global scale, it is crucial to consider CDVT adaptability to diverse infrastructures, technological advancements, financial requirements, and social acceptance. This will help determine their true capabilities and suitability in different regions worldwide.

Bibliometric analysis was additionally conducted to identify the most pertinent, impactful, and influential research related to the application

of CDVT. The purpose of this analysis was to gain a comprehensive understanding of the current state of research in this field and get a useful framework for organising and comprehending the different approaches that have been used in this area of study based on keywords and abstract of the selected research works. VOSviewer software was used to analyse the knowledge domain bibliometric track based on the co-occurrence of key terms for a specific unit of analysis (keywords, titles and abstracts), type of analysis (co-occurrence) and counting method (full counting). The results are shown in Fig. 2b-c. Fig. 2b shows the three clusters of all keywords in the selected research papers. The clusters of word groups were identified and visually represented using unified colours. Note that each cluster visually shows with a separate colour (i.e., grey, blue and orange). Frequency of occurrence of similar words is also reflected in the size of globe/font and hence the most frequently used word in each cluster is the focal point of the cluster with the largest size. In addition, the green globe ("3D visualisation") is the focal points (research scope) of all research papers representing three primary clusters as VR, AR, and DT. As such, the blue cluster represents research papers mainly focusing on the application or advancement of VR with a focus on dynamic expression of disasters and the role of behavioural intervention in public evacuation. The grey cluster represents AR research paper mainly involving the public through demonstration of flood events, field surveys, attending workshops, and showcase in mobile apps. Finally, the yellow cluster represents the DT applications emphasising vulnerability and risk assessment in urban policies and smart cities.

Similarly, Fig. 2c shows the timeframe of appearing those keywords in the research papers over the time mainly between 2018 and 2022. As such, the initial focus revolved around the interaction between risk assessment, disaster awareness with relevant technologies. As the time passed, there has been a shift towards prioritising risk communication and involving a broader range of stakeholders in flood risk management. More specifically, within the cluster of AR, there is a noticeable emphasis on the recent advancements of mixed reality, which seeks to establish connections between the dynamic expressions of VR and AR

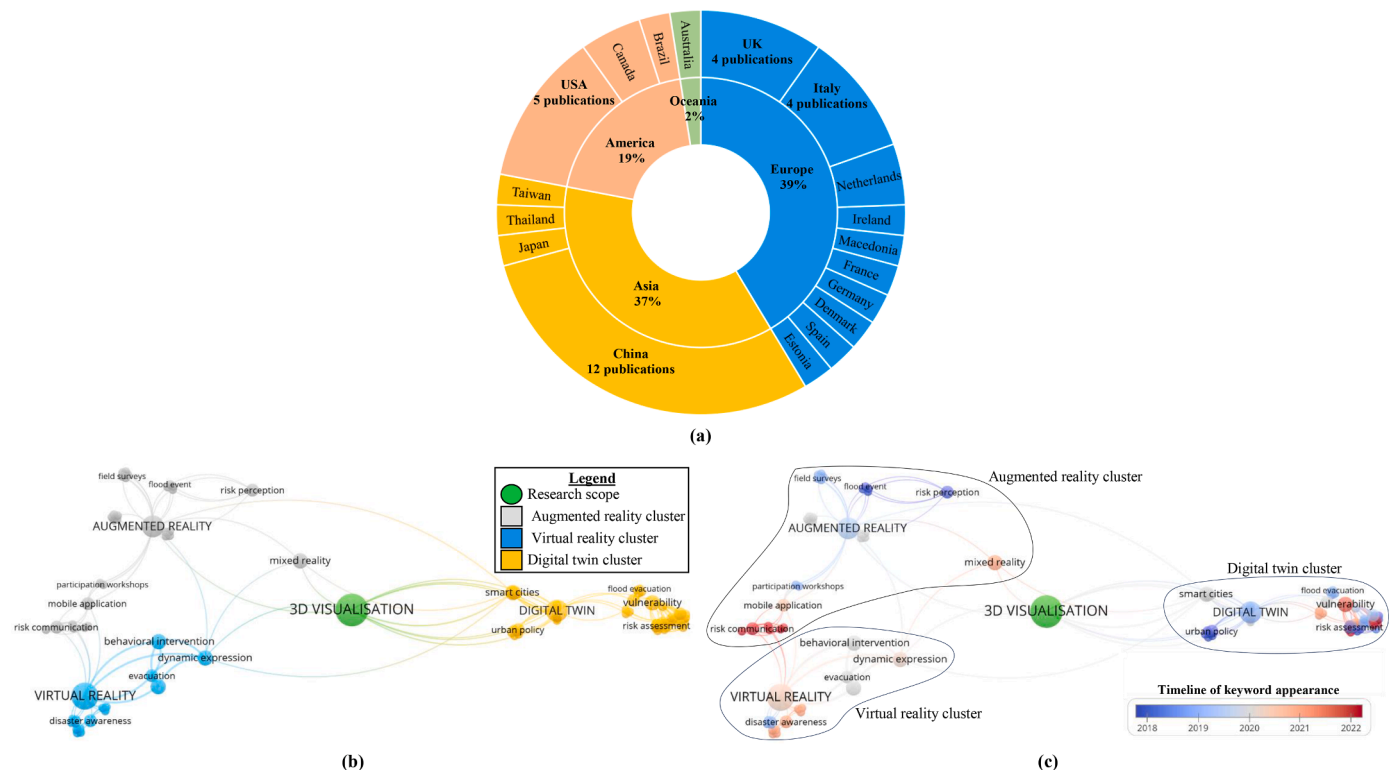


Fig. 2. Bibliometric analysis based on: (a) country of corresponding authors, (b) cluster and (c) timeframe of keywords in the collected papers

technologies. Furthermore, there has been a recent focus on risk communication through mobile applications. On the other hand, disaster awareness and vulnerability assessment gained more attention later on in the era of VR, while DT technologies have recently attracted more interest in the context of vulnerability assessment.

3. Types of CDVT

Based on the bibliometric analysis, the identified CDVT have been classified into three main categories: VR, AR, and DT. The application of these technologies is critically analysed in the following subsections, followed by an overall scientometric analysis.

3.1. Virtual reality technologies

Applied VR technologies are classified into three main classes based on their approach to visualise urban flooding and presenting relevant risk consequences. Initially, these tools were in the form of the printed or immersive 3D images, used widely in the web-based applications. They were then expanded into immersive dynamic environments and game-based visualisations, which are described in detail below.

3.1.1. Immersive 3D image and 3D Web-based visualisation

Immersive 3D images generally are digital images that create the sense of three-dimensional space and depth, providing a more realistic and interactive experience for the viewer. They are typically created using computer graphics and can be viewed through various devices such as head-mounted displays, computer screens, or mobile devices (De Santis et al., 2018). Immersive 3D images have been applied for two main purposes: (1) indicating the progress and expansion of the flood occurrence and (2) assessing the flood damage and vulnerability of urban structures. First approach provides 3D images of flood inundation which can be physically made via a 3D printer to visualise different flood levels (Burian et al., 2020). In the second approach, immersive 3D images can capture detailed information about the land and structures, including their spatial layout, dimensions, materials, and the surrounding topography (Amirebrahimi et al., 2016). By overlaying simulated flood conditions onto these 3D images, a comprehensive visual representation is created to show the impact of potential floods on the built environment and how flood parameters interact with the structures, providing valuable insights into flood vulnerabilities and potential risks (Aahlaad et al., 2021).

Alternatively, 3D web-based visualisation refers to the use of interactive 3D digital models to display information on a web platform. This technology allows users to view and manipulate 3D models of real-world objects or environments directly within their web browser, without the need for specialised software or hardware (Zhu et al., 2014). This approach employs web 3D technologies and online mapping tools such as Google Earth, Google Maps, and ArcGIS to develop software and apps that simulate and visualise floods through the creation of interactive virtual geographic environments. An open-source platform offers additional advantages, as it allows end-users, such as stakeholders, to remotely access flood management tools at any time. With this platform, stakeholders can conveniently access shared data from any location, facilitating quicker decision-making and enabling early action without the need for physical meetings. This accessibility and flexibility enhance collaboration and efficiency in flood management scenarios (Singh & Garg, 2016). Furthermore, the ease of use and accessibility of this method enables stakeholders to evaluate critical parameters such as flood arrival time, inundation area, and flood velocity in real-time for early action and make informed decisions rapidly (Van Ackere et al., 2016).

3.1.2. Immersive dynamic environment

The immersive dynamic environment is an advanced VR tool specifically developed to visualise floods, offering users to explore and

understand flood consequences in real-time but a controlled, safe, and risk-free manner (Yang et al., 2021). Immersive dynamic environments typically feature realistic water flow simulations, dynamic flooding, drainage systems, and weather patterns to create an environment that accurately replicates different flood scenarios, ranging from minor floods to extreme events (Wang et al., 2019). Two major objectives are identified here, as outlined in Table 2, including flood damage assessment and flood evacuation routing. VR-based flood damage assessment has gained significant attention due to its potential to integrate diverse building information and flood parameters effectively. This approach allows for the development of detailed 3D models of the built environment, enhancing realism and enabling more accurate assessments of potential flood damage. Hence, combining virtual reality technology with flood data can provide decision-makers with valuable insights in urban flood management (Schröter et al., 2018).

One of the significant VR advantages in flood damage assessment is the ability to identify areas at higher risk of flooding and assess the structural risks associated with buildings in those areas (Luo et al., 2021). Moreover, the use of 3D models enables users to identify structures that can be repaired or demolished and develop reconstruction strategies (Zhi et al., 2020). This information can be used to inform building design and construction methods to better withstand future floods.

On the other hand, immersive dynamic environments can be incorporated into the flood evacuation process by designing realistic and engaging simulations that immerse users in a VR environment simulating a flood event and crowd dynamics (Li et al., 2019), as shown in Table 2. These simulations can incorporate realistic water and sound effects, as well as other visual and auditory cues to make users feel that they are actually experiencing a flood (Jacquinod & Bonaccorsi, 2019). By developing open-source apps and simulating different flood scenarios, evacuation routes, and evacuation timing, users can test and evaluate the effectiveness of various evacuation strategies. This approach can help visualise the behaviour of various stakeholders, particularly victims, during floods, and enable the identification of appropriate evacuation facilities such as evacuation routes and assembly points (Macchione et al., 2019). Besides, cloud-based systems support collaboration and knowledge sharing among various stakeholders involved in flood management by providing access to robust computing resources and centralised platforms for data sharing and make it possible to create complex 3D models and simulations. Real-time data sources, such as weather forecasts and water level sensors, can also be seamlessly integrated into cloud-based platforms, enabling the generation of accurate and up-to-date flood models (Banfi et al., 2020).

3.1.3. Game-based visualisation

Game-based visualisation that gained considerable attention in recent years, offers users an interactive and engaging experience to better comprehend the potential impacts of flooding (Fujimi & Fujimura, 2020). The primary function of game-based VR technology in this context is to create a stimulating and exciting atmosphere for target audiences to experience the flood potential damages in a fun but engaging way into perception of the flood nature (Skinner, 2020). To achieve this, various flood simulation games, illustrated in Table 3, have been developed that provide task-based multi-optional gaming experiences and immerse stakeholders in realistic flood scenarios, such as river flooding and surface runoff, using tools such as head-mounted displays with stereoscopic views (Sermet & Demir, 2019). As a result, the decisions adopted by stakeholders during the game can be assessed, their judgments about flood damages can be evaluated, and the impact that these games have on the behaviour of these people can be tracked and followed up (Mol et al., 2022). This approach employs gameplay platforms to construct a more immersive environment, facilitating users' understanding of complex flood scenarios, along with their associated risks and consequences (Simpson et al., 2022). Although, immersive dynamic environments aim to be more realistic and precise, utilising

Table 2
Recent immersive virtual reality applied to urban flood risk management

| Aim | Method/ platform | Application | Main functions | Reference |
|---|--|---|--|---|
| Flood damage assessment | Dynamic 3D city flood damage simulation | River flooding | - Developing multi-variable flood loss models to characterise the buildings vulnerability - Estimation of flood losses to residential buildings virtual 3D city models, numerical spatial measures, and remote sensing data | Schröter et al. (2018) |
| | Dynamical digital earth flood risk platform 3D geo-visualisations | Surface runoff River flooding | - Developing fast-computational flood simulation in spatio-temporal GIS with 1D and 2D hydrodynamic models - Presenting water level using VR headset and smartphone | Wu et al. (2019) Jacquinod and Bonaccorsi (2019) Wang et al. (2019) |
| | Integrated simulation and 3D visualisation 3D dynamic surface water depth Cloud-based platform | River flooding Drainage system River flooding | - Investigating impact of various designed sponge city strategies on urban flooding - Obtaining 3D spatial buildings risks by coupling flood simulation models with 3D above-ground building models - Improving building management and monitoring systems in flood prone areas | Zhi et al. (2020) Banfi et al. (2020) |
| | Dynamic fusion disaster environment | River flooding | - Providing readable disaster information colours coded risks, flood depth signs, and dynamic flood direction - Adding more texture and layers such as housing, population, critical facilities, and road damage to 3D environment | Luo et al. (2021) |
| | 3D dynamic flood map | River flooding | - 3D hydrological real-time interactive platform - Displaying 3D perspective of water level, rain monitoring, flood evolution, submergence analysis, and disaster assessment | Yang et al. (2021) |
| | Tunnel vision | Surface runoff | - Efficient rendered flood scenes to provide disaster information and enhanced cognitive environment | Fu et al. (2021) |
| | Flood evacuation routing | Flood evacuation simulation | Surface runoff | - Modelling the flood and crowd dynamics to visualise public behaviour |
| Dynamic 3D open-source application Geospatial storytelling environment | | River flooding Surface runoff | - Identification of evacuation routes, assembly points, and people who would need to be evacuated - Providing flood multi-node story with combination of static and dynamic representation to show evacuation plans, rescue routes, and temporarily assembling points during-disaster education | Macchione et al. (2019) Li et al. (2022) |

Table 3
Recent game-based virtual reality applied to urban flood risk management

| Platform/game name | Application | Main functions | Reference |
|--------------------------------|----------------|---|----------------------------|
| “Flood action” | Surface runoff | - Task-based multi-optional game teaching required actions during disaster events | Sermet and Demir (2019) |
| “Flash Flood!” | River flooding | - Creating curiosity-based game about the various impacts of river flooding by simulating geo-morphology and fluvial flooding | Skinner (2020) |
| Experiment-based game | Surface runoff | - Investigating public behaviour in various flash flood evacuation scenarios | Fujimi and Fujimura (2020) |
| “FloodWargame” | Surface runoff | - Simulation of flood impacts on affected area and population | Su et al. (2021) |
| Dynamic risk-based environment | Surface runoff | - Immersive storm-surge flood scene highlighting damages and flood effects on environment | Simpson et al. (2022) |
| Flood hazard-based game | Surface runoff | - Head mounted display to boost risk perception, coping appraisal, negative emotions and damage-reducing behaviour | Mol et al. (2022) |

advanced simulation techniques to create an accurate and lifelike experience, game-based technologies aim to be highly interactive and engaging, leveraging gaming tools to create an immersive experience (Li et al., 2022).

3.2. Augmented reality technology

AR technology overlays computer-generated images onto the user’s real-world view, creating an interactive and immersive experience that

simulates and visualises flood events and their potential environmental impacts (Zhang et al., 2020). One of the primary platforms of AR is through mobile apps that are downloaded onto smartphones or tablets, as outlined in Table 4. These apps use the camera and sensors on the device to display real-time flood information, such as water levels, on top of a live video feed of the affected area. Some apps use in-situ 3D geometry modelling techniques to visualise surface runoff (Haynes & Lange, 2016a) or flood events along a riverside (Haynes & Lange, 2016b) in urban areas and highlight potential hazards. Others provide a higher level of on-site experience and engagement by integrating real-time building models with flood simulation for a more realistic representation (Haynes et al., 2018). Apps built on a client-server framework that incorporate GPS functionality, provide users with a broader range of options through integrating contextual information with the real-time environment. This information includes location-specific data such as flood warnings or evacuation routes, 3D visualisation of the most critical flood-prone areas, and simulated emergency scenarios. They integrate hydraulic and hydrological model simulation data on mobile devices, based on a client-server architecture where the smartphone client interacts with a server application (web service) through messages (Mirauda et al., 2018).

Computer software also can create AR experiences ranging from flood laboratory setting to visualise the flood impacts. AR software developers employ platforms such as touch tables or hybrid physical-numerical software, as demonstrated in Table 4, to generate 3D flood hazard maps and displaying potential flood progression on a landscape model named digital touch table (Tomkins & Lange, 2019). Furthermore, another AR system called HoloLens is employed to visualise the flooding event on a digital table, allowing users to interact with digital content using hand tracking options (Rydvanskiy & Hedley, 2021).

A hybrid software platform creates an experience that superimposes a virtual flood scene onto a 3D printed physical terrain model (Zhang et al., 2020). These platforms integrates numerical simulations with dynamic observation data collected from sensors embedded in a physical model of the flooding area. During or before running the programme, users can adjust parameters such as water flow, and the results

Table 4
Recent augmented reality applied to urban flood risk management

| Platform/ Software name | Application | Main functions | Reference | |
|--|--|--|---|------------------------------|
| Mobile apps | CSG | Surface runoff | - Adjustable flood depth using in-situ geometry to show potential riverside dangers | Haynes and Lange (2016a) |
| | Integrated HCI modelling app "MAR" app | River flooding | - Adjustable flood plain size and depth by tracking environment | Haynes and Lange (2016b) |
| | | River flooding | - Populating with occlusion geometry and occluding interactive flood plain | Haynes et al. (2018) |
| | Client-server framework | River flooding | - Real-time illustration of water observatory for IoT-based sensor readings | Mirauda et al. (2018) |
| | | - Offering engagement linking simulations with on-site experience | | |
| Digital touch tables | Multi-user terrain software | River flooding | - Visualising geo-referenced sensors such as gyroscope, compass, and GPS | Tomkins and Lange (2019) |
| | | | - Allowing mobile workforces to reach the critical areas | |
| Hybrid physical-numerical modules | HoloLens interface system | River flooding | - 3D visualisation of simulated emergency scenarios | Rydvanskiy and Hedley (2021) |
| | | | - Displaying potential flood progression onto a landscape | |
| | Collaborative VGE | River flooding | - Creating 3D flood hazard map | Li et al. (2015) |
| | | | - Showing flood prone areas in digital touch-tables | |
| Sandbox module | River flooding | - Integrable with surrounding environment while being stable and usable in real-world settings | Puertas et al. (2020) | |
| | | - Incorporation of data driven flood simulation and dynamic observational data to generate accurate flood events predictions | | |
| "FARV3DPT" software | Surface runoff | - Representing flood extension and magnitude over physical topography | Zhang et al. (2020) | |
| | | - Creating accurate visualisation environment | | |
| | | - Providing more intuitive flood hazards environment | | |

3D: 3-Dimension App; Application AR: Augmented reality CSG: Constructive Solid Geometry

DTM: Digital Terrain Model GPS: Global Positioning System HCI: Human Computer Interaction IoT: Internet of Things

MAR: Mobile AR VGE: virtual geographic environment

can be exported in various formats such as pictures, videos, audios, and texts (Li et al., 2015). Sandbox modules, which includes a physical scale topography, buildings, roads, and dikes produces a digital terrain model in real-time. By computing water flow via numerical methods and projecting the numerical model's outcomes onto the Sandbox, a "virtual water" experience is created that illustrates the spread of flooding in the physical model (Puertas et al., 2020).

3.3. Digital twin technologies

DT has been utilised in urban water systems for drainage, river flooding, and surface runoff applications (See Table 5). However, its full potential in covering the entire urban water cycle remains limited. The urban water cycle includes water supply, distribution, water/waste-water treatment, drainage systems. In the context of urban water visualisation, DT creates a virtual model of the system by combining data from various sources such as sensors, weather forecasts, and urban maps to create prototype DTs or constructing living DTs. During the planning phase, prototyping DT systems are established and utilised to design inherently safe urban drainage systems against floods (Bartos & Kerkez, 2021). On the other hand, through the operation phase, the living DT is employed to enable users to model and monitor the system in real-time,

predict and explore various flood scenarios and their potential repercussions, and effectively mitigate them (Pedersen et al., 2021). Furthermore, while mapping flood-prone areas with flood risk levels can be conducted through living DTs in drainage systems (Truu et al., 2021),

Alternatively, DT is employed for simulating the impact of floods on urban areas in the context of a smart city through creating a virtual model of a city, incorporating its buildings, critical infrastructure, and topography (Ford & Wolf, 2020). The DT can then be utilised to simulate various flood scenarios, such as heavy rainfall, river overflows, or surface runoff (Deren et al., 2021). The simulation can be continuously updated with data from sensors installed throughout the city, allowing the DT to provide up-to-date information on the current state of flood, the location of flood-prone areas, the flow and level of water through the city, and the potential impacts of flooding public safety (White et al., 2021). Additionally, the DT system utilises historical flood and rainfall data, as well as topographical information, to establish a timeline of flood occurrences and develop testable, rapid, and reliable early warning systems (Ghaith et al., 2022). As a result, the outcomes of the smart city DT can be utilised extensively in urban planning, including establishing distributed flood hazard and risk assessment maps and implementing emergency simulations for flood prevention and mitigation measures (Wang et al., 2022).

Table 5
Recent digital twin applied to urban flood risk management

| visualisation type | Developed plot | Application | Main functions | Reference |
|---|--|---|--|--------------------------|
| Urban water system visualisation | Multi-layer supervision framework "Pipedream" toolkit | Urban water cycle | - Dividing cyber-physical system into four the layers of supervision control, scheduling, water users, and environment layer | Sun et al. (2020) |
| | | Drainage systems | - Real-time control model Detecting pre-emptively to repair blockages, leaks and other required maintenance emergencies. | Bartos and Kerkez (2021) |
| | Prototyping and living framework Planning support system | Drainage systems | - System control and operation including surface runoff, infiltration, and water load | Pedersen et al. (2021) |
| | | Drainage systems | - Risk-based mapping of flood prone areas | Truu et al. (2021) |
| Smart city visualisation | Living error diagnosis framework | Drainage systems | - Analysing the impact of climate change on new and existing infrastructure | Pedersen et al. (2022) |
| | | | - Providing a scheme for classification of errors and uncertainties | |
| | Smart city platform | River flooding | - Identifying roles and source of uncertainties and errors in performance | White et al. (2021) |
| | | | - Dynamic timeline of flood occurrence | |
| Smart city platform | Surface runoff | - Flood projection used for urban evacuation, alerting citizens, and identifying inaccessible roads and pavements | Ghaith et al. (2022) | |
| | Surface runoff | - City visualisation reflecting 3D building data, characteristics of critical infrastructures, and public behaviour | | |
| | Smart city platform | Surface runoff | - Digitalising the storm surge hazards to provide distributed danger and risk assessment maps | Wang et al. (2022) |

3.4. Technology-based scientometric analysis

Analysing the trends indicated in Fig. 3a and b reveals that despite VR being the most extensively explored technology with 59% of total selected research works, its dominance in this field may be attributed to its early adoption and well-established infrastructure. In contrast, AR has shown a relatively lower percentage of research studies with 23%. However, the consistent presence of AR as a technology of interest signifies its potential value in this research area. As illustrated in Fig. 3b, AR is still being explored and its full potential is yet to be realised. Future advancements in AR technology, such as improved tracking and seamless integration with real-world environments, may unlock new possibilities for visualising and understanding floods. On the other hand, the relatively lower percentage of studies focused on DT (19%) indicates that this emerging technology is still in its early stages of exploration. However, the significant attention garnered by DT over the past three years, as shown in Fig. 3b, suggests its growing recognition as a valuable tool for visualising floods. The use of DTs, which simulate real-world environments and phenomena, holds promise for providing detailed and accurate representations of flood scenarios.

As illustrated in Fig. 3c, the integration of CDVT has been observed in four key areas within urban systems, namely river flooding, surface runoff, drainage system, and the urban water cycle. Among these areas, river flooding has received the most extensive attention. VR has been the most utilised technology in this area, providing users with a realistic experience, allowing them to better comprehend the potential impacts of river flooding, such as inundation and erosion. The application of surface runoff visualisation has witnessed a notable surge in attention in recent years, with a particular focus on the utilisation of VR technology.

The preference for VR in surface runoff can be attributed to its immersive nature that create detailed and visually compelling representations of surface runoff processes and dynamics. Visualisation of flood impacts in urban drainage systems has also been explored, with both VR and DT technologies being employed. However, DT has contributed more significantly to the visualisation in this area. By creating a real-time and interactive representation of the drainage system, DT provides monitoring of how flooding affects the system's performance. This includes visualising potential issues such as blockages, overflows, and the overall hydraulic behaviour under flood conditions. Finally, despite the importance of the urban water cycle, only one research article focused on the visualisation of its flood impacts. This study utilised DT technology to provide a real-time visualisation of the urban water cycle during a flood event, enabling users to better understand the potential impacts of floods on the entire urban water system, including water supply, collection, and sanitation.

All selected research works have followed three main key objectives through using CDVT, including flood damage assessment, flood evacuation routing, and flood inundation simulation (See Fig. 3d). VR has been the primary tool for damage assessment studies, owing to its ability to create a 3D model of a flood and its impact on buildings. However, limited research has been conducted on this objective using AR and DT technology. This gap represents a significant opportunity in the field, as these technologies have the potential to offer an interactive experience for researchers to visualise flood damage in an intuitive way. Regarding flood evacuation routing, Fig. 3d indicates that VR is the most used technology for this purpose, but there is a lack of studies exploring the potential of AR and DT in this context. Therefore, further research is needed to determine the efficacy of these technologies in practical

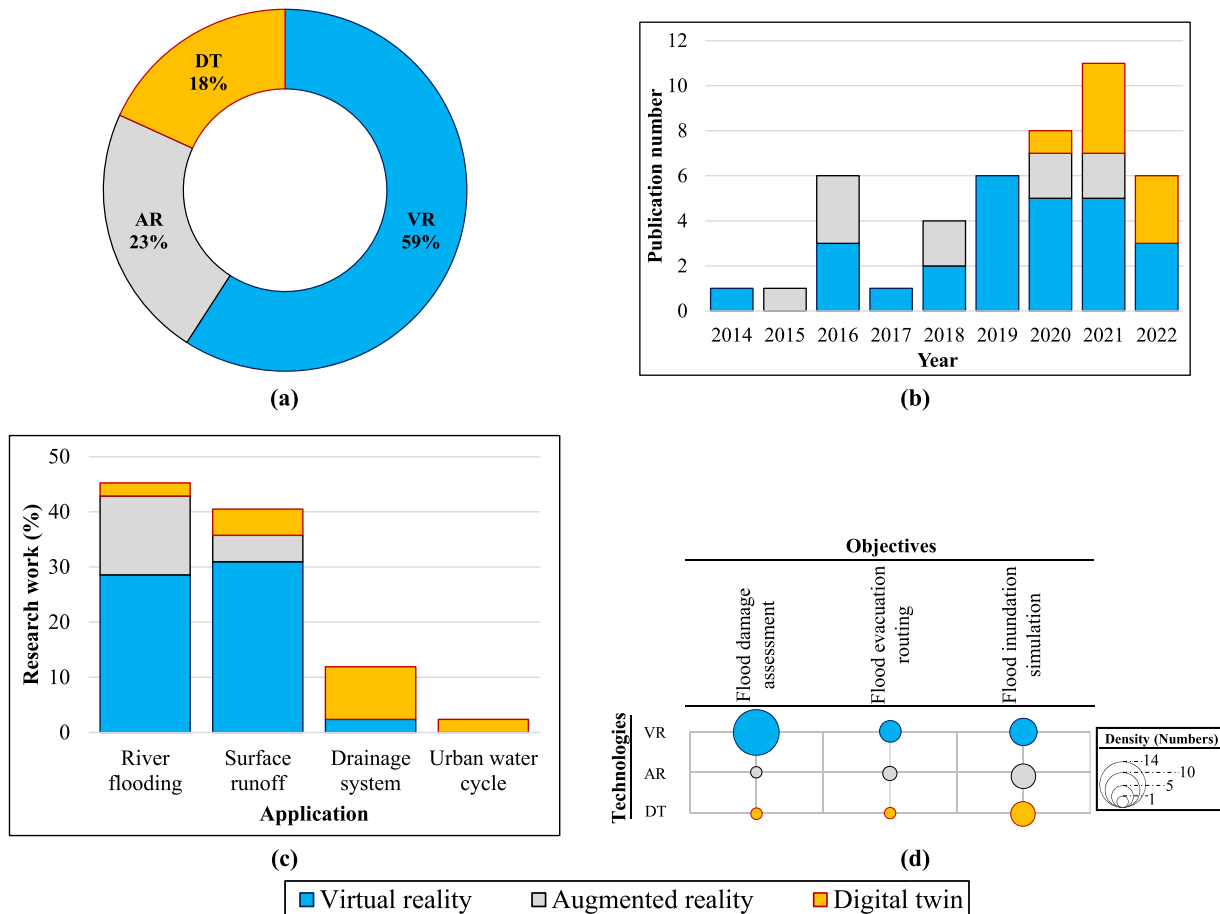


Fig. 3. Dashboard of the recent digital visualisation technologies: (a) proportional breakdown, (b) timeline distribution, (c) application distribution, (d) objective distribution

applications, such as evacuation routing, and to identify potential areas for improvement. Flood inundation simulation has also been explored using VR, AR, and DT. Fig. 3d demonstrated a balanced representation of these technologies, showcasing the diverse array of approaches and tools for visualising floods. Each technology brings its unique strengths and capabilities to the field, enabling researchers and stakeholders to gain insights into different aspects of flood behaviour and impacts.

4. Visualisation of urban flood risk management

Urban flood risk management is the process of identifying, assessing, and controlling the risk of flooding in urban areas, which involves a diverse range of measures aimed at reducing the probability and severity of flood consequences, as well as preparing for and responding to flood events when they occur (Kittipongvises et al., 2020). Effective flood risk management involves long-term coordination and collaboration among stakeholders to allocate resources efficiently and determine roles and responsibilities for mitigation and resilience (Kuhlicke et al., 2020). As such, flood visualisation is an essential and critical tool that offers stakeholders a better understanding of flood scenarios, enabling them to comprehend the progression of the event and its potential impacts on people, assets, and the environment (Heinzle et al., 2020).

4.1. Role of digital visualisation in urban flood risk management

Table 6 summarises the major roles, contributions, and applications of CDVT to various stages of urban risk management with relevant references. CDVT can be efficiently used at prevention stage to facilitate communication with stakeholders and communities for better planning and design of infrastructure and hence avoiding flood risk. For cases that flood is unavoidable, CDVT can be used at mitigation stage for collaborative decision making and testing out various scenarios to reduce the severity and consequences of flood events. Before the flood events, CDVT can be efficiently linked with contemporary real-time flood forecasting systems to issue early warning for early action when the flood is imminent (Piadeh et al. 2022). The potential of community awareness of CDVT can be further explored by involving communities and stakeholders in the decision making and scenario analysis. As post-flood efforts, CDVT can also be effectively used for rescuers and those in flood risk to minimise the human and financial losses. Finally, CDVT can contribute to recovery measures to return communities to normal conditions quickly and thus enhancing flood resilience for communities and infrastructure in flood-prone areas (Shah et al., 2018).

CDVT can play a crucial role by visually representing flood-prone areas, flood patterns, and potential impacts (Oubennaceur et al., 2021). It supports proactive measures in prevention and mitigation, facilitates monitoring and response efforts during flood events, and aids in damage assessment and post-flood recovery planning. Besides, these tools can empower decision-makers, emergency responders, and communities to better understand the risks they face, make informed choices, and coordinate actions effectively (Cheung & Feldman, 2019). By visualising crucial flood-related data, including flood extent, depth, and forecasted scenarios, stakeholders can gain a comprehensive understanding of the situation, prioritise actions, allocate resources, and plan for both short-term response and long-term mitigation efforts. Furthermore, recent advancements in real-time flood forecasting involve the integration of machine learning techniques, enhancing the accuracy of predictions (Piadeh et al. 2023). Combining these forecasting models with digital visualisation can help early warning systems as more efficient tools for communities and decision-makers to allow for prompt early actions that would minimise damages and improve flood risk management.

4.2. Flood risk-based scientometric analysis

Table 6
Role of digital visualisation in various stages of urban flood risk management

| Risk management stage | Purpose | Contribution of digital visualisation to flood risk management | References |
|-----------------------|--|---|--|
| Prevention | Avoiding flood occurrence | <ul style="list-style-type: none"> - Risk communication: Presents complex information in a more accessible and comprehensible way, thereby enhancing public awareness - Land use planning: Helps to indicate the potential consequences of diverse land use decisions, such as constructing structures within flood-prone zones or modifying drainage systems, thereby assisting in minimising flood risks - Designing inherently safe infrastructure: Assists in simulating a range of flood scenarios, thereby facilitating the determination of optimal size and location for flood control infrastructure, aiming to prevent flood occurrences | <p>Macchione et al. (2019)</p> <p>Wang et al. (2019)</p> <p>Rydvanskiy and Hedley (2021)</p> |
| Mitigation | Controlling, minimising, or reducing adverse impacts of unavoidable floods | <ul style="list-style-type: none"> - Collaborative Decision-Making: Provides a shared virtual environment for interactive collaboration - Scenarios testing: Facilities in analysing mitigation strategy effectiveness, optimising flood control measures, and assessing long-term flood risk reduction impact | <p>Li et al. (2015)</p> <p>Sermet and Demir (2019)</p> |
| Preparation | Increasing communities ability and capability for appropriate response in flood occurrence | <ul style="list-style-type: none"> - Early warning systems: Aids in presenting flood forecasts or evacuation routes, in an easily understandable format - Situational awareness: Provides immersive experiences for emergency responders to gain a deeper understanding of the flood's magnitude, speed, and potential impacts - Community participation: Facilities collaborative decision-making in which stakeholders can explore various flood mitigation options, and foster a sense of ownership and involvement | <p>Zhu et al. (2014)</p> <p>Fujimi and Fujimura (2020)</p> <p>Mol et al. (2022)</p> |
| Response | Actions carried to save lives, protect | <ul style="list-style-type: none"> - Response coordination: Creates | <p>Haynes et al. (2018)</p> |

(continued on next page)

Fig. 4 presents distribution of applied CDVT in each flood risk

Table 6 (continued)

| Risk management stage | Purpose | Contribution of digital visualisation to flood risk management | References |
|-----------------------|--|--|--|
| | assets, reduce losses, and alleviate suffering | virtual command centres where decision-makers can collaborate remotely by visualising real-time data, monitoring the situation, and communicating with field responders - Planning: Helps in developing more robust emergency response plans by creating virtual models of the flood-prone areas and simulating various flood scenarios - Training and Education: Provides on-the-job guidance by overlaying relevant information onto the real-world context and training emergency responders | Mirauda et al. (2018) Yang et al. (2021) |
| Recovery | Actions taken to return a community to normal conditions | - Damage Assessment: Creates virtual replicas of flood-affected areas, enabling detailed damage assessment, helping authorities prioritise recovery efforts, allocating resources effectively, and developing targeted plans for reconstruction - Remote Collaboration: Facilitates remote collaboration among recovery teams and experts through overlay virtual information onto the physical environment - Reconstruction: Visualise proposed reconstruction plans in a simulated environment to better understand the envisioned changes during the recovery process | Schröter et al. (2018) Wang et al. (2019) Wang et al. (2022) |

management stage for the selected research works. As illustrated in Fig. 4a, it is evident that these technologies are being developed to tackle the challenges of flood risk management, with an increased emphasis on preparation and mitigation measures. More than 30% of the selected studies focus on the preparation stage, indicating substantial interest and investment in tools that can assist communities in preparing for flood events and reducing their devastating impact. The second-highest proportion of research works is directed towards the mitigation stage, with less than 30% of efforts focused on decreasing the severity and consequences of flooding events. This implies that CDVT is better suited for the stages around the time of flood occurrence, particularly in the preparation and mitigation stages. Specific measures supported by CDVT during these stages include flood monitoring and forecasting platforms, early warning systems, and early action measures. By leveraging CDVT, decision-makers can improve flood preparedness,

enhance real-time monitoring, and implement timely responses, thus effectively mitigating the impacts of floods and improving overall flood risk management.

Subsequently, selected studies have focused on the response stage, accounting for more than 20%. The use of CDVT at this stage plays an important role in visualisation studies, enabling stakeholders to prepare for flood events and coordinate response efforts effectively. By providing real-time data for real-time flood forecasting coupled with data driven and machine learning techniques (Piadeh et al., 2023), visualisation capabilities in CDVT can considerably empower decision-makers to make informed choices, plan appropriate responses, and enhance overall flood preparedness and resilience. Effectively to increase public awareness of imminent flood risks, prompting early action that can significantly mitigate financial losses, injuries, and fatalities. By providing visual and real-time information to the public, CDVT empowers individuals and communities to take proactive measures and make informed decisions during flood events, contributing to better flood resilience and reduced human and economic impacts.

Finally, the results show that studies have devoted the least attention to the prevention and recovery stages, with only around 15% and 5%, respectively. This outcome can be attributed to several reasons. Firstly, flood visualisation research often concentrates on immediate response to flooding events, such as evacuation planning and real-time flood monitoring. These two stages may be perceived as less urgent and, as a result, receive less attention. Furthermore, prevention and recovery stages may necessitate more complicated and long-term solutions, such as land-use planning and flood-proofing buildings. These types of solutions may require interdisciplinary collaboration and long-term funding, which can be challenging to execute in practice.

Fig. 4b illustrates the focus of the selected studies on different flood risk management stages. A significant portion (70%) have addressed more than one stage of flood risk management, indicating that researchers recognise the versatile potential of these technologies across various stages of flood risk management. By employing these tools, they aim to enhance various aspects of risk management, including comprehending, decision-making, communication, and assessment of flood-related risks and impacts. Furthermore, 28% of the studies focused on addressing only one specific stage of flood risk management. These studies may have targeted a particular phase, such as prevention or response, to delve deeper into the challenges and opportunities associated with that specific stage. This focused approach allows researchers to investigate the unique requirements and potentials of each stage, tailoring their visualisation efforts accordingly. On the other hand, a small percentage (2%) of the studies have addressed all stages comprehensively. These studies likely aimed to provide a holistic approach to flood visualisation, considering the interdependencies and interactions among prevention, mitigation, preparation, response, and recovery. By encompassing all stages, these comprehensive studies offer valuable insights into the potential synergies and trade-offs among different risk management strategies, supporting integrated flood risk management approaches.

Fig. 4c displays the distribution of the applied CDVT across various stages of flood risk management. The Figure reveals that VR has notably focused on the preparation stage, followed by the response and mitigation stages. The immersive and realistic nature of VR allows stakeholders to practice response strategies, evaluate evacuation plans, and enhance preparation for potential flood events. This makes VR a valuable tool for training and simulations in flood preparation. The response stage has also received significant attention, as VR enables stakeholders to visualise real-time flood conditions, monitor impacts, and coordinate response efforts. By providing a realistic representation of the flood situation such as machine learning to forecast real-time water level in urban drainage systems (Piadeh et al., 2023), VR can effectively help stakeholders enhance decision-making and situational awareness for the public just before and during flood events. Similarly, the mitigation stage has gained considerable focus, with VR being used to visualise and

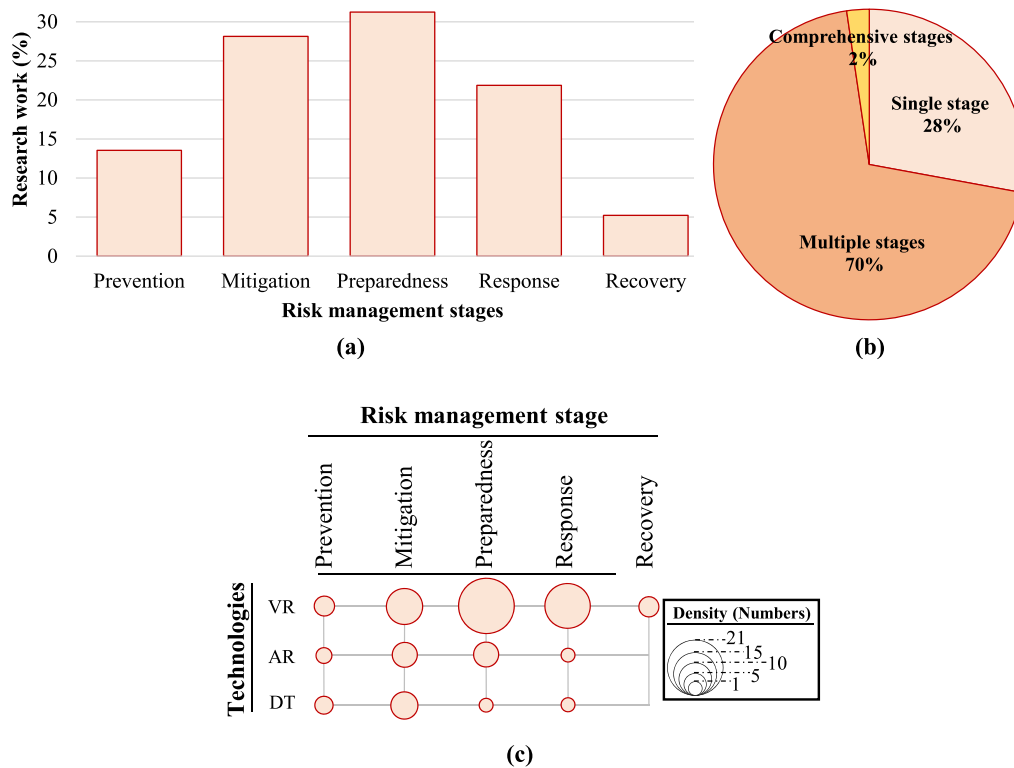


Fig. 4. Dashboard highlighting recent digital visualisation technologies implemented across various stages of urban flood risk management: (a) distribution of research studies across risk management stages, (b) focused risk management stage, (c) Bubble plot of applications within each risk management stage

assess the effectiveness of flood mitigation measures, facilitating the evaluation of strategies for reducing flood impacts. In contrast, the prevention and recovery stages have received less attention. The prevention stage, which involves long-term measures to prevent or minimise the occurrence of floods, may pose challenges for visualisation due to the complex and time-dependent nature of preventive actions. Similarly, the recovery stage, addressing post-flood restoration and rehabilitation, involves a wide range of activities that may not lend themselves as directly to visualisation.

According to Fig. 4c, studies on the application of AR technology in flood risk management have been distributed relatively evenly across four stages (i.e., prevention, mitigation, preparation, and response), but there is no studies focusing on the recovery stage. Focusing on these four stages implies the potential use of AR in multiple stages, particularly from pre-flood measures to immediate response actions. On the other hand, as the recovery stage involves activities such as damage assessment, infrastructure restoration, community rehabilitation, and long-term recovery planning, researchers may have focused on the stages where immediate impact can be achieved to highlight the effectiveness of AR tool. However, the absence of studies in this area may indicate a research gap, which is worth exploring given the significance of the recovery stage in achieving sustainable and resilient post-flood communities.

Finally, the majority of studies on the application of DT technology in flood risk management have focused on the mitigation stage. This is likely due to the potential of DT in supporting decision-making for flood risk reduction and management through simulating and testing various mitigation strategies. In contrast, the number of studies conducted on the prevention, preparation, and response stages were relatively similar. These stages can also benefit from DT technology, such as identifying flood-prone areas, predicting flood events, and providing real-time information during a flood event. Conversely, no study has been conducted on the recovery stage using DT. The lack of studies focusing on this stage may also indicate a research gap or a potential area for further

exploration and development of DT in flood risk management as DT can play a role in supporting the recovery stage by providing stakeholders with detailed information on the extent of flood damage and assisting in decision-making process for prioritising recovery efforts.

5. Limitations of CDVT in urban flood risk management

These limitations can be attributed to three main categories including technical limitations, cost and resource limitations, and user and accessibility limitations. More specifically, these technologies often involve complex algorithms, simulations, and integration of various data sources. Developing and maintaining such systems requires expertise in fields such as computer vision, 3D modelling, and real-time data processing and analytics e.g., forecasting. Ensuring the seamless integration of different technologies and maintaining system performance can be technically demanding (Kikuchi et al., 2022). Additionally, implementing these technologies may need a significant amount of accurate and up-to-date data, such as topographical data, hydrological data, and flood modelling information to provide reliable outputs (Botín-Sanabria et al., 2022). Although data collection from various sources (e.g., ground, radar and satellite) are more accessible, obtaining comprehensive and accurate data can be challenging, particularly in urban areas with complex infrastructure and varying levels of data availability.

Furthermore, implementing these technologies often requires significant investments in infrastructure, including hardware, software, and data infrastructure. This can be cost-prohibitive for many urban areas, especially those with limited financial resources or existing infrastructure challenges (Simpson et al., 2022). Acquiring and maintaining the necessary data can also be expensive, including costs associated with data collection, sensor networks, remote sensing technologies, and ongoing data management and updates (Bartolini et al., 2018). Limited financial resources may hinder access to the required data or lead to outdated or incomplete datasets. Moreover, effectively utilising these technologies requires skilled personnel with

expertise in data analysis, modelling, and visualisation techniques (Perera et al., 2020). However, training and retaining personnel with these specialised skills can be challenging. On the other hand, while CDVT offer valuable insights, they may not be accessible to all stakeholders involved in flood risk management, especially community members and non-technical personnel. Limited access to the necessary hardware, software, or training can hinder the widespread adoption and use of these technologies (Calil et al., 2021).

6. Conclusions

This study provides a critical review of cutting-edge digital visualisation technologies that are applied in urban flood risk management. Three individual technologies, i.e., VR, AR, and DT, have been identified and their application have been critically analysed within the five stages of urban flood risk management. Furthermore, flood damage assessment, flood evacuation routing, and flood inundation simulation are considered as key objectives of applying CDVT in urban flood risk management. The following can be noted as the main findings:

- VR emerged as the most used technology with three main classes identified, including immersive 3D images, immersive dynamic environments, and game-based visualisations. AR obtained the second-highest proportion, mainly focusing on river flooding visualisation. DT received less attention, representing a significant opportunity for further investigation in these areas.
- The utilisation of CDVT was observed across the four domains of urban water infrastructure, including urban rivers, surface runoff, drainage systems, and urban water cycle although more attention is needed to focus on the entire urban water infrastructure and their components to achieve flood resilience.
- Unlike the well-explored use of VR technology for flood damage assessment, there remains a significant gap in the literature for the use of AR and DT for this purpose. These technologies have the potential to improve real-time data visualisation, facilitate communication and collaboration, and enhance interactive experiences.
- Real-time data availability for infrastructure and environmental conditions, coupled with data-driven modeling such as machine learning, offers a unique opportunity to integrate with CDVT. This enables valuable real-time flood forecasting, benefiting stakeholders and the public by enhancing early warning, preparedness and resilience to floods.
- Simulating urban flood inundation and flood evacuation routes is recognised as a promising direction for future research in this field, as it can provide valuable information to improve risk communication, enhance emergency response planning, develop better flood mitigation strategies, and increase community resilience to future flood events.
- Preparation and mitigation stages have been the primary focus of research on CDVT in flood risk management, with comparatively less attention given to the prevention and recovery stages. This underscores the necessity for further investigation into these stages as without a comprehensive understanding of prevention and recovery stages, risk management strategies may fall short of fully addressing the complex challenges posed by flooding. This underestimation can lead to increased economic losses, environmental damage, and social disruption.

This study provided a comprehensive overview of the current state of CDVT in urban flood risk management, highlighting gaps in the literature and future research directions. This study is limited to published journal or conference papers that present conceptual or practical applications of CDVT. However, it is acknowledged that many recent advances are being used on an industrial scale by municipalities, water companies, and regional and national agencies. These efforts are often patented or not publicly accessible in detail and therefore cannot be

tracked or accessed to extract the necessary information. Future research should consider the latest advancements in CDVT and collaborate with relevant sectors to develop an inclusive approach for applying these technologies in urban flood risk management. In addition, research works on these technologies predominantly focus on highlighting their strengths and advantages. This is primarily due to the relatively new nature of these technologies. While existing research highlights the strengths and advantages of these technologies, there is still a gap in the literature regarding their practical implementation and potential drawbacks. However, there is a need for more studies that examine the extent to which these tools are truly beneficial and address the challenges and limitations associated with their use. Further investigation into the effectiveness, limitations, and potential issues related to these technologies would provide valuable insights and help in shaping their future development and application.

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.

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 and the three anonymous reviewers for making constructive comments which substantially improved the quality of the paper.

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.
- 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.
- Banfi, F., Previtali, M., & Brumana, R. (2020). Towards the development of a cloud-based BIM platform and VR apps for complex heritage sites subject to the risk of flood and water level changes. *IOP Conference Series: Materials Science and Engineering*, 12105.
- Bartolini, S., Mecocci, A., Pozzebon, A., Zoppetti, C., Bertoni, D., Sarti, G., Caiti, A., Costanzi, R., Catani, F., Ciampalini, A., & Moretti, S. (2018). Augmented virtuality for coastal management: A holistic use of in situ and remote sensing for large scale definition of coastal dynamics. *ISPRS International Journal of Geo-Information*, 7(3), 92.
- Bartos, M., & Kerkez, B. (2021). Pipedream: An interactive digital twin model for natural and urban drainage systems. *Environmental Modelling & Software*, 144, Article 105120.
- Botín-Sanabria, D. M., Mihaita, A. S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., & Lozoya-Santos, J. D. J. (2022). Digital twin technology challenges and applications: A comprehensive review. *Remote Sensing*, 14(6), 1335.
- 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.
- Calil, J., Fauville, G., Queiroz, A. C. M., Leo, K. L., Newton Mann, A. G., Wise-West, T., Salvatore, p., & Bailenson, J. N (2021). Using virtual reality in sea level rise planning and community engagement-an overview. *Water*, 13(9), 1142.
- Carver, S. (2019). Developing Web-based GIS/MCE: Improving access to data and spatial decision support tools. *Spatial multicriteria decision making and analysis* (pp. 49–76). Routledge.

- Cheung, W., & Feldman, D. (2019). Can citizen science promote flood risk communication? *Water*, 11(10), 1961.
- Ciullo, A., Viglione, A., Castellarin, A., Crisci, M., & Di Baldassarre, G. (2017). Socio-hydrological modelling of flood-risk dynamics: comparing the resilience of green and technological systems. *Hydrological sciences journal*, 62(6), 880–891.
- CREED (Centre for Research on the Epidemiology of Disasters). (2022). Emergency events database. [Online] Available at emdat.be [Accessed 04/01/2023].
- Da Silva, L. B. L., Humberto, J. S., Alencar, M. H., Ferreira, R. J. P., & de Almeida, A. T. (2020). GIS-based multidimensional decision model for enhancing flood risk prioritization in urban areas. *International Journal of Disaster Risk Reduction*, 48, Article 101582.
- Deren, L., Wenbo, Y., & Zhenfeng, S. (2021). Smart city based on digital twins. *Computational Urban Science*, 1, 1–11.
- De Santis, R., Macchione, F., Costabile, p., & Costanzo, C. (2018). A comparative analysis of 3-D representations of urban flood map in virtual environments for hazard communication purposes. In , 40. *Proceedings of the E3S web of conferences* (p. 06037). EDP Sciences.
- Ford, D., & Wolf, C. (2020). Smart cities with digital twin systems for disaster management. *Journal of Management in Engineering*, 36(4), Article 4020027.
- Fu, L., Zhu, J., Li, W., Zhu, Q., Xu, B., Xie, Y., Zhang, Y., Hu, Y., Lu, J., Dang, p., & 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.
- 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.
- Guo, K., Guan, M., & Yu, D. (2021). Urban surface water flood modelling—a comprehensive review of current models and future challenges. *Hydrology and Earth System Sciences*, 25(5), 2843–2860.
- Hamil, L. (2011). *Understanding hydraulics* (3rd ed., pp. 507–585). London: Macmillan Education.
- Haynes, P., & Lange, E. (2016a). In-situ flood visualisation using mobile AR. In *Proceedings of the IEEE symposium on 3D user interfaces (3DUI)* (pp. 243–244).
- Haynes, P., & Lange, E. (2016b). 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.
- Heinzl, F., Becue, V., & Serre, D. (2020). A spatial decision support system for enhancing resilience to floods: Bridging resilience modelling and geovisualization techniques. *Natural Hazards and Earth System Sciences*, 20(4), 1049–1068.
- Huang, Y., Tian, Z., Ke, Q., Liu, J., Irannezhad, M., Fan, D., Hou, M., & Sun, L. (2020). Nature-based solutions for urban pluvial flood risk management. *Wiley Interdisciplinary Reviews: Water*, 7(3), e1421.
- International Water Association (IWA) (2019). Digital water: Industry leaders chart the transformation journey [online]. Available from <https://iwa-network.org/publications/digital-water/> (Accessed 30 June 2023).
- Jacquino, F., & Bonaccorsi, J. (2019). Studying social uses of 3D geovisualizations: lessons learned from action-research projects in the field of flood mitigation planning. *ISPRS International Journal of Geo-Information*, 8(2), 84.
- Kikuchi, N., Fukuda, T., & Yabuki, N. (2022). Future landscape visualization using a city digital twin: Integration of augmented reality and drones with implementation of 3D model-based occlusion handling. *Journal of Computational Design and Engineering*, 9(2), 837–856.
- Kittipongvises, S., Phetrak, A., Rattanapun, p., Brundiers, K., Buizer, J. L., & Melnick, R. (2020). AHP-GIS analysis for flood hazard assessment of the communities nearby the world heritage site on Ayutthaya Island, Thailand. *International Journal of Disaster Risk Reduction*, 48, Article 101612.
- Kuhlicke, C., Seebauer, S., Hudson, p., Begg, C., Bubeck, p., Dittmer, C., Grothmann, T., Heidenreich, A., Kreibich, H., Lorenz, D. F., & Masson, T. (2020). The behavioral turn in flood risk management, its assumptions and potential implications. *Wiley Interdisciplinary Reviews: Water*, 7(3), e1418.
- Lei, B., Janssen, p., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. *Automation in Construction*, 147, Article 104716.
- 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, Y., Gong, J., Song, Y., Liu, Z., Ma, T., Liu, H., Shen, S., Li, W., & 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.
- Li, Y., Hu, B., Zhang, D., Gong, J., Song, Y., & Sun, J. (2019). Flood evacuation simulations using cellular automata and multiagent systems—a human-environment relationship perspective. *International Journal of Geographical Information Science*, 33(11), 2241–2258.
- 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.
- Ma, C., Zhao, Y., AL-Dohuki, S., Yang, J., Ye, X., Kamw, F., & Amiruzzaman, M. (2020). GTMapLens: Interactive lens for geo-text data browsing on map. *Computer Graphics Forum*, 39(3), 469–481.
- 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.
- Mai, T., Mushtaq, S., Reardon-Smith, K., Webb, p., Stone, R., Kath, J., & An-Vo, D. A. (2020). Defining flood risk management strategies: A systems approach. *International Journal of Disaster Risk Reduction*, 47, Article 101550.
- Martyr-Koller, R., Thomas, A., Schleussner, C. F., Nauels, A., & Lissner, T. (2021). Loss and damage implications of sea-level rise on small island developing states. *Current Opinion in Environmental Sustainability*, 50, 245–259.
- 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), Article 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.
- Muthalif, M., Shojaei, D., & Khoshelham, K. (2022). A review of augmented reality visualisation methods for subsurface utilities. *Advanced Engineering Informatics*, 51, Article 101498.
- 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.
- Perera, D., Seidou, O., Agnihotri, J., Mehmood, H., & Rasmy, M. (2020). Challenges and technical advances in flood early warning systems (FEWSs). *Flood impact mitigation and resilience enhancement* (p. 19). London, UK: IntechOpen.
- Pesantez, J., Alghamdi, F., Sabu, S., Mahinthakumar, G., & Berglund, E. (2022). Using a digital twin to explore water infrastructure impacts during the COVID-19 pandemic. *Sustainable Cities and Society*, 77, Article 103520.
- Piadeh, F., Behzadian, K., Chen, A. S., Campos, L. C., Rizzuto, J. P., & Kapelan, Z. (2023). Event-based decision support algorithm for real-time flood forecasting in urban drainage systems using machine learning modelling. *Environmental Modelling & Software*, Article 105772.
- Piadeh, F., Behzadian, K., & Alani, A. (2022). A critical review of real-time modelling of flood forecasting in urban drainage systems. *Journal of Hydrology*, 607, Article 127476.
- Puertas, J., Hernández-Ibáñez, L., Cea, L., Regueiro-Picallo, M., Barneche-Naya, V., & Varela-García, F. A. (2020). An augmented reality facility to run hybrid physical-numerical flood models. *Water*, 12(11), 3290.
- Ramu, S., Boopalan, p., Pham, Q., Maddikunta, p., Huynh-The, T., Alazab, M., Nguyen, T., & Gadekallu, T. (2022). Federated learning enabled digital twins for smart cities: Concepts, recent advances, and future directions. *Sustainable Cities and Society*, 79, Article 103663.
- Rydvanskiy, R., & Hedley, N. (2021). Mixed reality flood visualizations: reflections on development and usability of current systems. *International Journal of Geo-Information*, 10(2), 82.
- Saurav, K. C., Shrestha, S., Ninsawat, S., & Chonwattana, S. (2021). Predicting flood events in Kathmandu Metropolitan City under climate change and urbanisation. *Journal of Environmental Management*, 281, Article 111894.
- Schröter, K., Lütke, S., Redweik, R., Meier, J., Bochow, M., Ross, L., Nagel, C., & Kreibich, H. (2018). Flood loss estimation using 3D city models and remote sensing data. *Environmental Modelling & Software*, 105, 118–131.
- Sermet, Y., & Demir, I. (2019). Flood action VR: a virtual reality framework for disaster awareness and emergency response training. In *Proceedings of the 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.
- Shah, M. A. R., Rahman, A., & Chowdhury, S. H. (2018). Challenges for achieving sustainable flood risk management. *Journal of Flood Risk Management*, 11, S352–S358.
- 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.
- Skinner, C. (2020). Flash Flood!: A SeriousGeoGames activity combining science festivals, video games, and virtual reality with research data for communicating flood risk and geomorphology. *Geoscience Communication*, 3(1), 1–17.
- 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.
- Tomkins, A., & Lange, E. (2019). Interactive landscape design and flood visualisation in augmented reality. *Multimodal Technologies and Interaction*, 3(2), 43.
- Towe, R., Dean, G., Edwards, L., Nundloll, V., Blair, G., Lamb, R., Hankin, B., & Manson, S. (2020). Rethinking data-driven decision support in flood risk management for a big data age. *Journal of Flood Risk Management*, 13(4), e12652.
- 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.
- Van Ackere, S., Glas, H., Beullens, J., Deruyter, G., De Wulf, A., & De Maeyer (2016). Development of a 3D dynamic flood Web GIS visualisation tool. In *Proceedings of the 5th international conference on flood risk management and response (FRIAR 2016)* (pp. 560–569), 3.

- Wang, C., Hou, J., Miller, D., Brown, I., & Jiang, Y. (2019). Flood risk management in sponge cities: The role of integrated simulation and 3D visualization. *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.
- White, G., Zink, A., Codecá, L., & Clarke, S. (2021). A digital twin smart city for citizen feedback. *Cities*, 110, Article 103064.
- Xia, H., Liu, Z., Efremochkina, M., Liu, X., & Lin, C. (2022). Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modelling integration. *Sustainable Cities and Society*, 84, Article 104009.
- Yang, B., Ma, J., Huang, G., & Cao, D. (2021). Development and application of 3D visualization platform for flood evolution in Le'an River Basin of Wuyuan. *IOP Conference Series: Earth and Environmental Science*, 638(1), Article 012053.
- Zhang, G., Gong, J., Li, Y., Sun, J., Xu, B., Zhang, D., Zhou, J., Guo, L., Shen, S., & Yin, B. (2020). An efficient flood dynamic visualization approach based on 3D printing and augmented reality. *International Journal of Digital Earth*, 13(11), 1302–1320.
- Zhi, G., Liao, Z., Tian, W., & Wu, J. (2020). Urban flood risk assessment and analysis with a 3D visualization method coupling the PP-PSO algorithm and building data. *Journal of Environmental Management*, 268, Article 110521.
- 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, Y., & Li, N. (2021). Virtual and augmented reality technologies for emergency management in the built environments: A state-of-the-art review. *Journal of Safety Science and Resilience*, 2(1), 1–10.