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

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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

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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

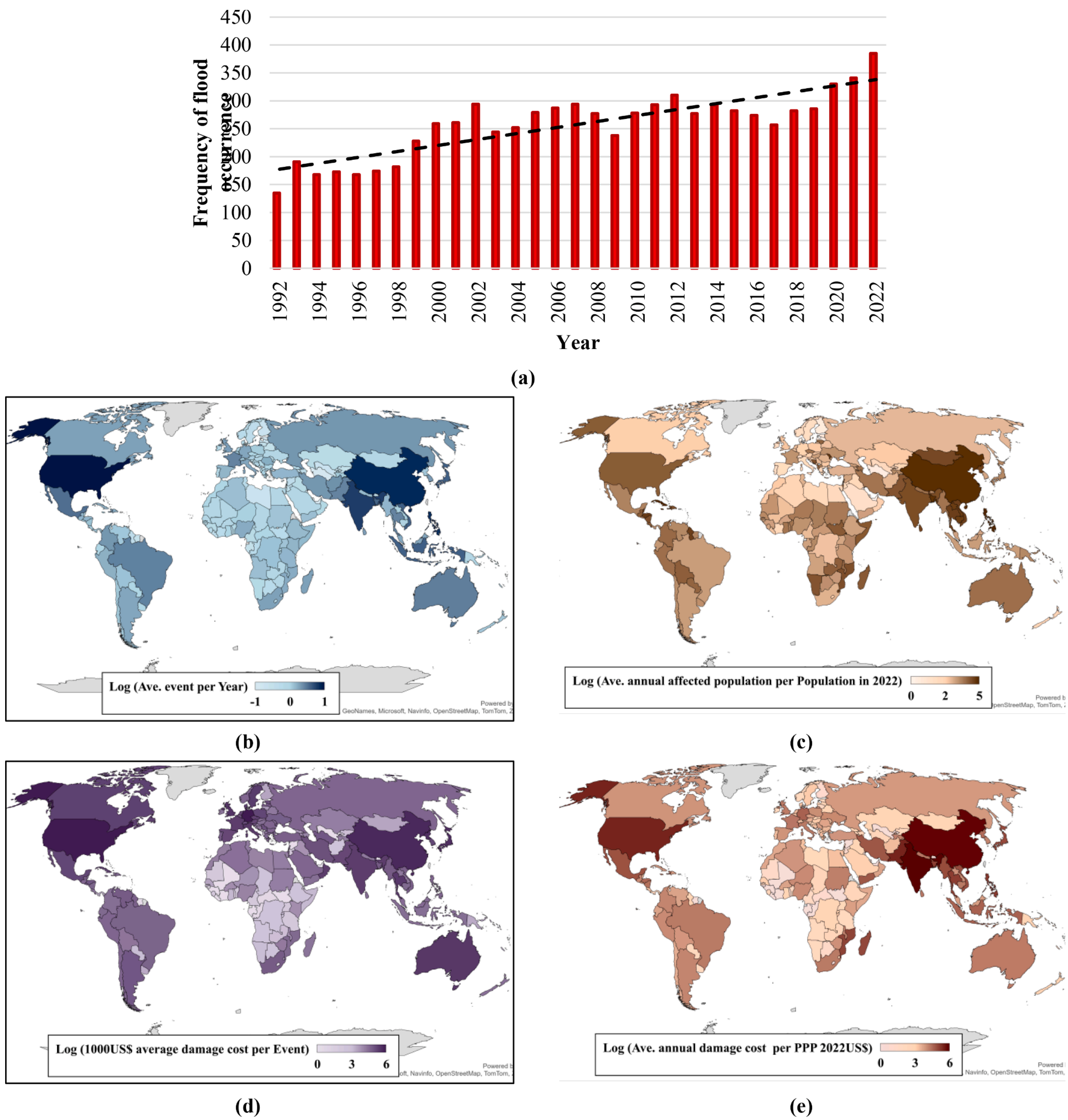

Fig. 1. Recorded urban flood events over the past 30 years: (a) historic trend of frequency of major flood events, (b) average annual flood occurrence, (c) average of annual affected population per population of country in 2022, (d) average damage cost estimated per event, and (e) average of annual damage 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 (S_1-S_4) were applied to narrow down the search results. The search results began with 891 publications in the first stage (S_1), which were gradually narrowed down in stages S_2 and S_3 with 43 studies identified for applied digital visualisation of urban flooding (S_3). Finally, 40 studies were identified in the fourth stage (S_4) 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

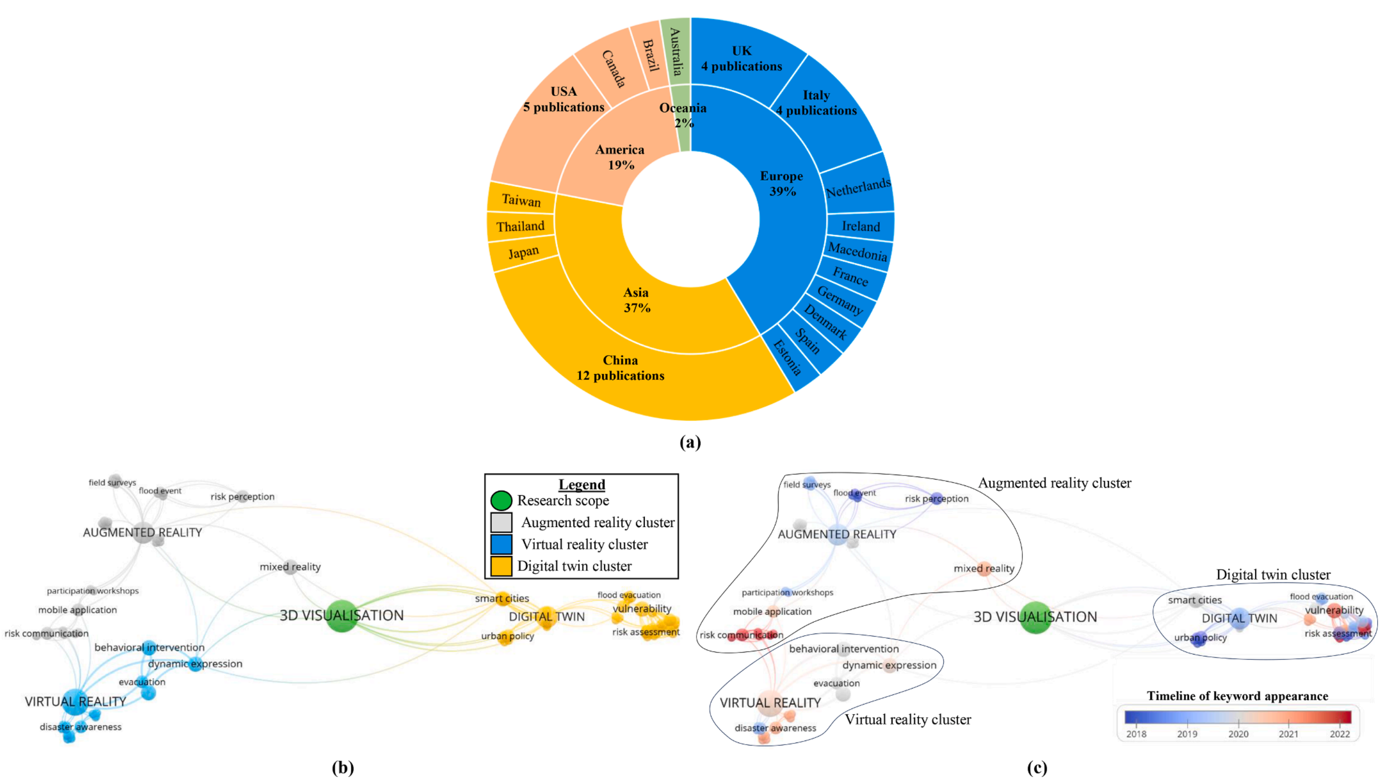

Fig. 2. Bibliometric analysis based on: (a) country of corresponding authors, (b) cluster and (c) timeframe of keywords in the collected papers

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 mains 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	Surface runoff	- Developing fast-computational flood simulation in spatio-temporal GIS with 1D and 2D hydrodynamic models	Wu et al. (2019)
	3D geo-visualisations	River flooding	- Presenting water level using VR headset and smartphone	Jacquinod and Bonaccorsi (2019)
	Integrated simulation and 3D visualisation	River flooding	- Investigating impact of various designed sponge city strategies on urban flooding	Wang et al. (2019)
	3D dynamic surface water depth	Drainage system	- Obtaining 3D spatial buildings risks by coupling flood simulation models with 3D above-ground building models	Zhi et al. (2020)
	Cloud-based platform	River flooding	- Improving building management and monitoring systems in flood prone areas	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	Li et al. (2019)
	Dynamic 3D open-source application	River flooding	- Identification of evacuation routes, assembly points, and people who would need to be evacuated	Macchione et al. (2019)
	Geospatial storytelling environment	Surface runoff	- 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	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	River flooding	- Adjustable flood plain size and depth by tracking environment - Populating with occlusion geometry and occluding interactive flood plain	Haynes and Lange (2016b)
	"MAR" app	River flooding	- Real-time illustration of water observatory for IoT-based sensor readings - Offering engagement linking simulations with on-site experience	Haynes et al. (2018)
	Client-server framework	River flooding	- Visualising geo-referenced sensors such as gyroscope, compass, and GPS - Allowing mobile workforces to reach the critical areas - 3D visualisation of simulated emergency scenarios	Mirauda et al. (2018)
Digital touch tables	Multi-user terrain software	River flooding	- Displaying potential flood progression onto a landscape - Creating 3D flood hazard map - Showing flood prone areas in digital touch-tables	Tomkins and Lange (2019)
	HoloLens interface system	River flooding	- Integrable with surrounding environment while being stable and usable in real-world settings	Rydvanskiy and Hedley (2021)
Hybrid physical-numerical modules	Collaborative VGE	River flooding	- Incorporation of data driven flood simulation and dynamic observational data to generate accurate flood events predictions	Li et al. (2015)
	Sandbox module	River flooding	- Representing flood extension and magnitude over physical topography	Puertas et al. (2020)
	"FARV3DPT" software	Surface runoff	- Creating accurate visualisation environment - Providing more intuitive flood hazards environment	Zhang et al. (2020)

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/wastewater 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	Urban water cycle	- Dividing cyber-physical system into four the layers of supervision control, scheduling, water users, and environment layer	Sun et al. (2020)
	"Pipedream" toolkit	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	Drainage systems	- System control and operation including surface runoff, infiltration, and water load	Pedersen et al. (2021)
	Planning support system	Drainage systems	- Risk-based mapping of flood prone areas - Analysing the impact of climate change on new and existing infrastructure	Truu et al. (2021)
	Living error diagnosis framework	Drainage systems	- Providing a scheme for classification of errors and uncertainties - Identifying roles and source of uncertainties and errors in performance	Pedersen et al. (2022)
Smart city visualisation	Smart city platform	River flooding	- Dynamic timeline of flood occurrence - Flood projection used for urban evacuation, alerting citizens, and identifying inaccessible roads and pavements	White et al. (2021)
	Smart city platform	Surface runoff	- City visualisation reflecting 3D building data, characteristics of critical infrastructures, and public behaviour	Ghaith et al. (2022)
	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

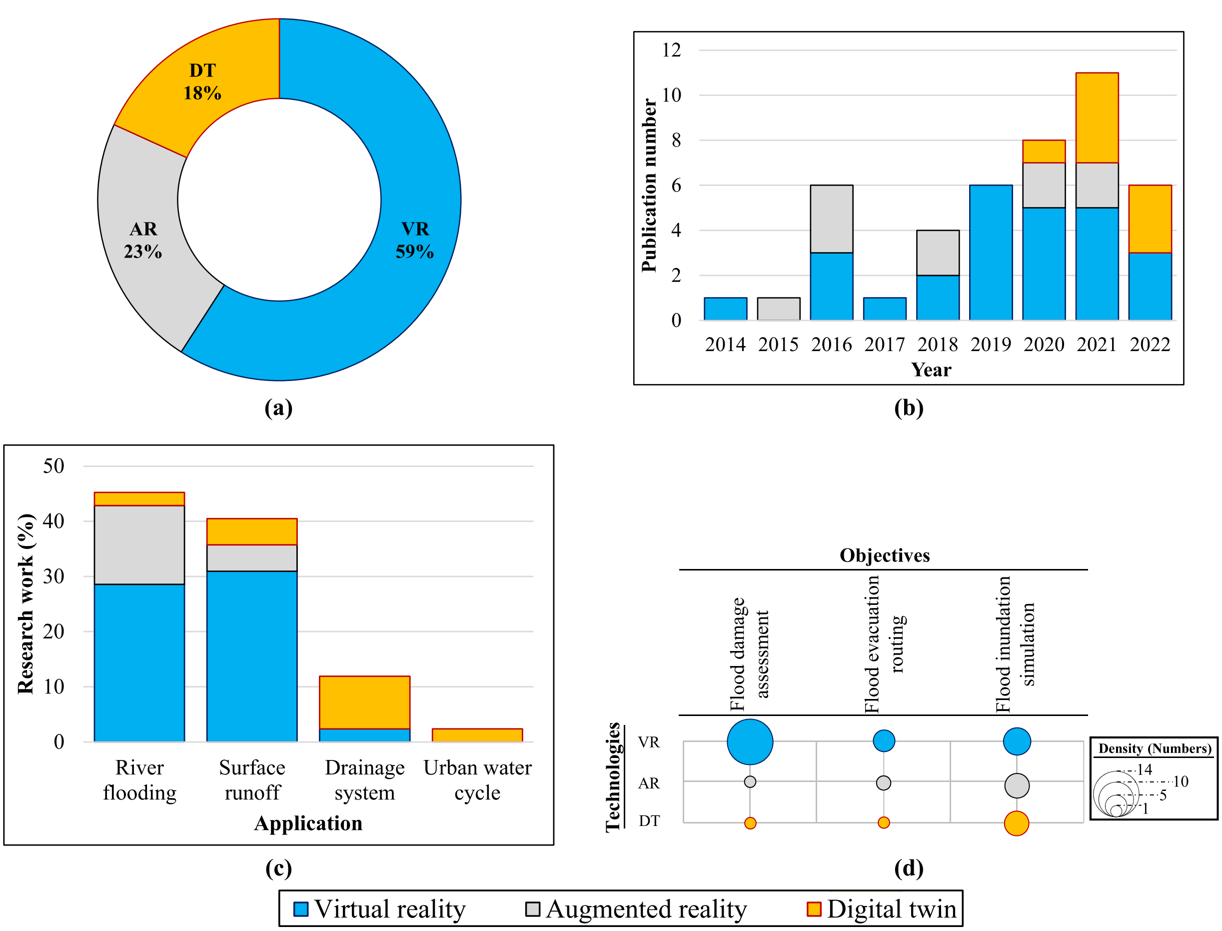

Fig. 3. Dashboard of the recent digital visualisation technologies: (a) proportional breakdown, (b) timeline distribution, (c) application distribution, (d) objective distribution

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 (Heinzlef 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

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

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	- Risk communication: Presents complex information in a more accessible and comprehensible way, thereby enhancing public awareness	Macchione et al. (2019)
		- 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	Wang et al. (2019)
		- 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	Rydvanskiy and Hedley (2021)
Mitigation	Controlling, minimising, or reducing adverse impacts of unavoidable floods	- Collaborative Decision-Making: Provides a shared virtual environment for interactive collaboration	Li et al. (2015)
		- Scenarios testing: Facilities in analysing mitigation strategy effectiveness, optimising flood control measures, and assessing long-term flood risk reduction impact	Sermet and Demir (2019)
Preparation	Increasing communities ability and capability for appropriate response in flood occurrence	- Early warning systems: Aids in presenting flood forecasts or evacuation routes, in an easily understandable format	Zhu et al. (2014)
		- Situational awareness: Provides immersive experiences for emergency responders to gain a deeper understanding of the flood's magnitude, speed, and potential impacts	Fujimi and Fujimura (2020)
		- Community participation: Facilities collaborative decision-making in which stakeholders can explore various flood mitigation options, and foster a sense of ownership and involvement	Mol et al. (2022)
Response	Actions carried to save lives, protect	- Response coordination: Creates	Haynes et al. (2018)

(continued on next page)

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	Mirauda et al. (2018)
		- Training and Education: Provides on-the-job guidance by overlaying relevant information onto the real-world context and training emergency responders	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	Schröter et al. (2018)
		- Remote Collaboration: Facilitates remote collaboration among recovery teams and experts through overlay virtual information onto the physical environment	Wang et al. (2019)
		- Reconstruction: Visualise proposed reconstruction plans in a simulated environment to better understand the envisioned changes during the recovery process	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

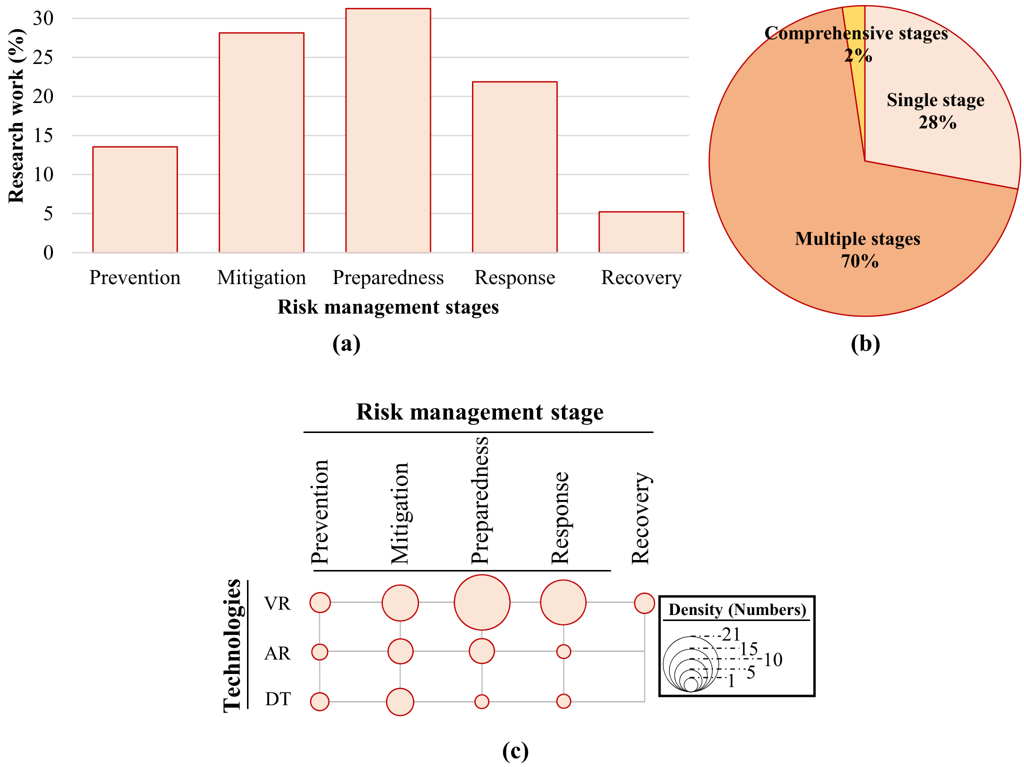

Fig. 4. Dashboard highlighting recent digital visualisation technologies implemented across various stages of urban flood risk management: (a) distribution of research studies across risk management stages, (b) focused risk management stage, (c) Bubble plot of applications within each risk management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

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