International Journal of Disaster Risk Reduction 100 (2024) 104151

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

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

A critical review of digital technology innovations for early warning of water-related disease outbreaks associated with climatic hazards

Cristiane D. Girotto[a], Farzad Piadeh[b], Vahid Bkhtiari[c], Kourosh Behzadian[a,d,*], Albert S. Chen[e], Luiza C. Campos[d], Massoud Zolgharni[a]

[a] School of Computing and Engineering, University of West London, St Mary's Road, Ealing, London, W5 5RF, UK
[b] Centre for Engineering Research, School of Physics, Engineering and Computer Science, University of Hertfordshire, Hatfield, AL10 9AB, UK
[c] Civil and Environmental Engineering Department, Amirkabir University of Technology, Hafez St., Tehran, 15875-4413, Iran
[d] Centre for Urban Sustainability and Resilience, Department of Civil, Environmental and Geomatic Engineering, University College London, London WC1E6BT, United Kingdom
[e] Faculty of Environment, Science and Economy, University of Exeter, Harrison Building, Streatham Campus, N Park Rd, Exeter, EX4 4QF, UK

ARTICLE INFO

Keywords:
Digitalisation
Digital application
Disease outbreaks
Early warning systems
Extreme weather

ABSTRACT

Water-related climatic disasters pose a significant threat to human health due to the potential of disease outbreaks, which are exacerbated by climate change. Therefore, it is crucial to predict their occurrence with sufficient lead time to allow for contingency plans to reduce risks to the population. Opportunities to address this challenge can be found in the rapid evolution of digital technologies. This study conducted a critical analysis of recent publications investigating advanced technologies and digital innovations for forecasting, alerting, and responding to water-related extreme events, particularly flooding, which is often linked to disaster-related disease outbreaks. The results indicate that certain digital innovations, such as portable and local sensors integrated with web-based platforms are new era for predicting events, developing control strategies and establishing early warning systems. Other technologies, such as augmented reality, virtual reality, and social media, can be more effective for monitoring flood spread, disseminating before/during the event information, and issuing warnings or directing emergency responses. The study also identified that the collection and translation of reliable data into information can be a major challenge for effective early warning systems and the adoption of digital innovations in disaster management. Augmented reality, and digital twin technologies should be further explored as valuable tools for better providing of communicating complex information on disaster development and response strategies to a wider range of audiences, particularly non-experts. This can help to increase community engagement in designing and operating effective early warning systems that can reduce the health impact of climatic disasters.

1. Introduction

Climatic hazards can have a significant impact on human and socioeconomic activities, leading to issues such as water shortages, limited access to clean water, psychological trauma, famine, and malnutrition caused by the destruction of agricultural land and dis-

* Corresponding author. School of Computing and Engineering, University of West London, St Mary's Road, Ealing, London, W5 5RF, UK.
E-mail address: kourosh.behzadian@uwl.ac.uk (K. Behzadian).

https://doi.org/10.1016/j.ijdrr.2023.104151
Received 14 March 2023; Received in revised form 15 October 2023; Accepted 20 November 2023
Available online 28 November 2023

rupted food supplies [1]. Basically, water-related climatic hazards (WRCH) can be divided into short-term events (e.g., flooding, cyclones, typhoons, hurricanes, heavy downpours, snowmelts) or long-term ones (e.g. drought and water scarcity). Either of these two event types can pose either immediate or long-lasting risks to human health, environment and infrastructures [2]. Over the last 50 years, as illustrated in Fig. 1, short-term climatic hazard events account for 64 % of total natural hazard events and almost 60 % of the affected population [3]. The death rate of 25 % (or 1 in 4) vividly illustrates the profound impacts of these disasters on society. These include the human tragedy and trauma experienced by affected individuals and communities, the loss of valuable human resources, and the economic setbacks that necessitate a long-term period of recovery [4].

WRCH can give rise to a diverse array of bacterial, viral, pest, or parasite infections, as shown in Fig. 2, due to disease transmission facilitated by environmental disruption, resource pollution, limited access to healthcare, and damaged critical infrastructure and services [5,6]. Moreover, post-event crowding can lead to the spread of diseases such as meningitis and acute respiratory infections. Vector-borne diseases, such as malaria and dengue, and tetanus can also be associated with extreme climatic events [7]. Several factors can contribute to this, such as the increased frequency of extreme weather events worldwide, contamination of water sources, and proliferation of mosquitoes [8,9].

Disease outbreaks can be further exacerbated when mental illnesses such as anxiety, depression, and schizophrenia emerge within survivor populations grappling with disruption, loss of social support, or post-traumatic stress disorders [12]. Furthermore, traumatic injuries such as fractures, lacerations, and contusions, as well as exposure to debris carried by floodwaters and the risk of electrocution in affected areas, can increase the vulnerability of individuals to open wounds, raising the potential for transmission of the aforementioned diseases [11].

To address these challenges, a wide variety of effective interventions have been introduced, encompassing structural construction and non-structural solutions [13]. However, structural solutions, while effective in mitigating certain challenges, can inadvertently contribute to increased CO_2 emissions. This occurs through construction activities, material usage, land use changes, and natural resource consumption, thereby exacerbating the adverse effects of climate change [14], as illustrated in Fig. 3. This linkage between structural solutions and the heightened frequency and severity of water-related extreme hazards due to climate change necessitates a shift in approach. To break/minimise this cycle, there is a critical need to explore non-structural solutions, especially early warning systems (EWS) and digital technology innovations (DTI) which involve the development and implementation of strategies aimed at preventing and mitigating the impact of extreme climatic events on the environment, infrastructure, and the health and well-being of communities as well as minimising or zero contribution to climate change, aligning with global net-zero emissions objectives and adaptation plans pursued by various countries [15].

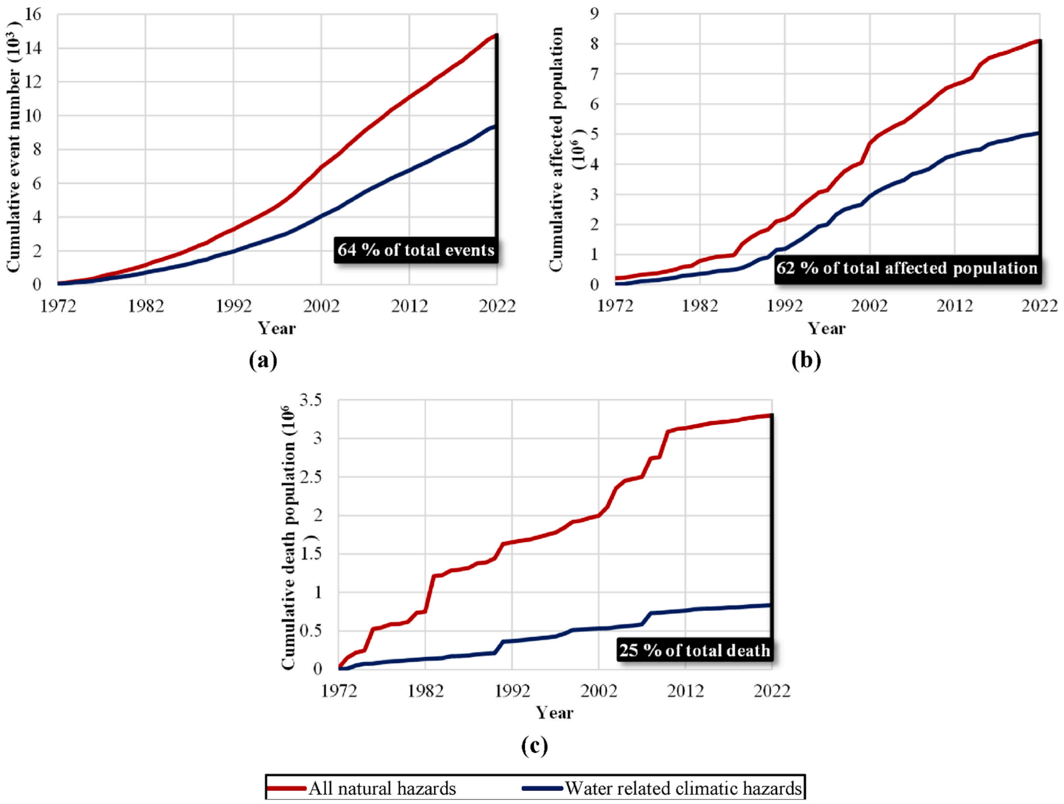

Fig. 1. Comparison between shot-term water-related climatic hazards with all natural hazards records accumulated over the last 50 years by (a) frequency, (b) affected population and (c) deaths (Raw data source [3].

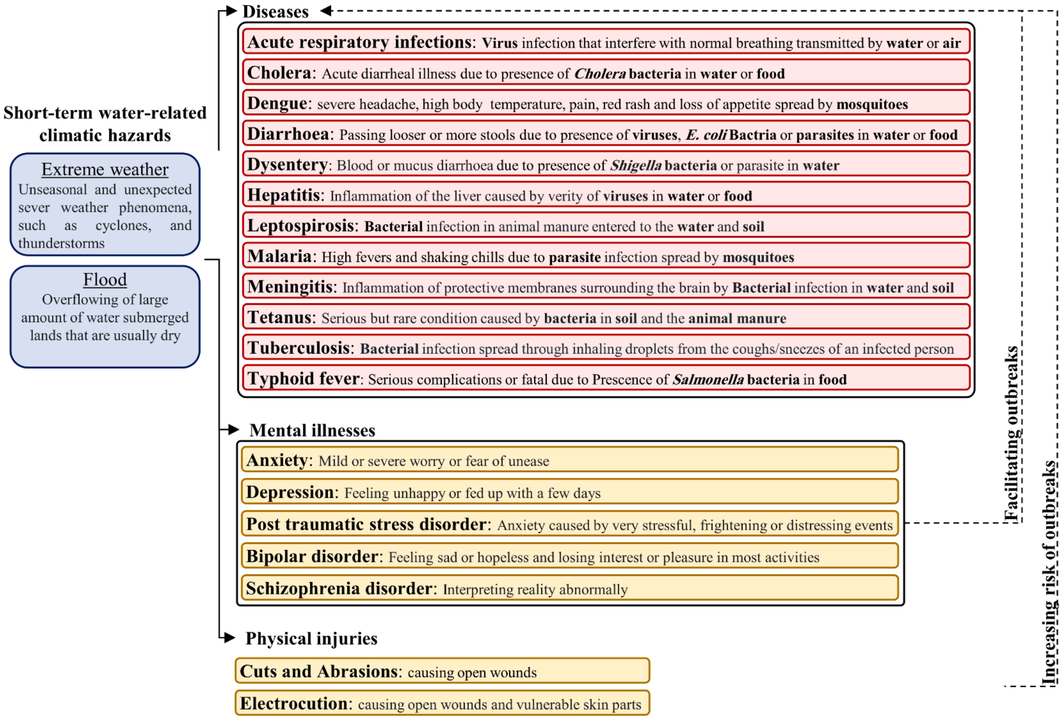

Fig. 2. Shot-term water-related climatic hazards and their association with the outbreak of diseases (raw data collected from Ref. [10]; Met office, 2022 [11,5].

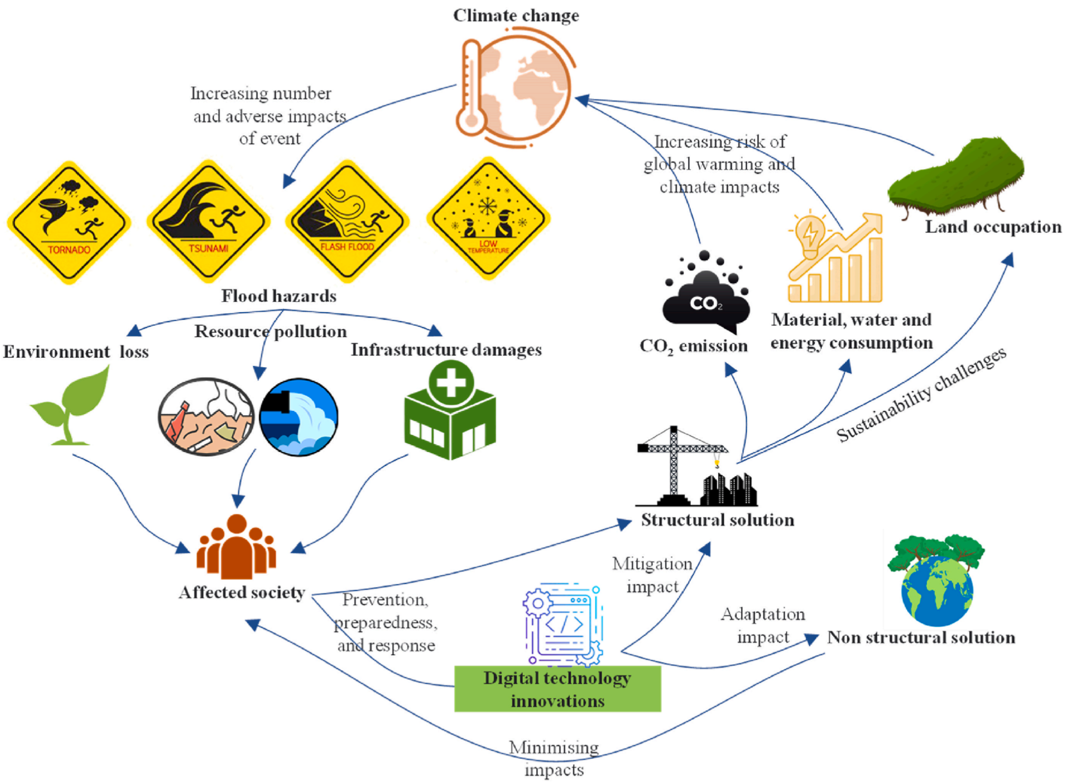

Fig. 3. Role of digital technology innovations in disease outbreaks.

The [16] defines EWS as an integrated system that encompasses hazard monitoring, forecasting and prediction, disaster risk assessment, communication, and preparedness activities, which enable individuals, communities, governments, businesses, and others to take timely action to reduce disaster risks before hazardous events occur. The application of these EWS have been extensively studied in the context of disaster forecasting, damage assessment, inundation, and evacuation planning [17,18]. These research works highlight the applications of drones and remote sensing for natural disaster management [19], real-time modelling of urban flooding predictions [20], and artificial intelligence (AI) technologies for disaster management [21]. Their advantages also explicitly have been reviewed including improving data collection and monitoring, hazard forecasting and risk reduction, enhanced communication and public awareness, smart infrastructure and property protection, resilience planning, enhancing emergency response, and accessibility of critical information [22,23]. Despite the plethora of digital technologies available for managing climatic hazards, their application for connecting climatic hazards to disease outbreaks is, as best of authors know, rarely emphasised.

A few research works focus on the relationship between diseases and climatic hazards, such as the role of EWS in dengue management [24], the dermatological conditions linked to extreme weather [25], the broader analysis of climate-sensitive infectious diseases that follow extreme climatic events [26], and the detection of common infectious diseases and health risk factors after a natural disaster [27]. However, cutting-edge digital technologies used for data collection, prediction, and EWS of short-term climatic hazards which can serve as a foundation for warning against any relevant disease outbreaks still needs more investigation.

To address this, the current study aims to review emerging digital technology innovation with concrete and potential applications for EWS in short-term climatic hazards. The study investigates how these technologies can contribute to reducing and controlling the risk of disease outbreaks and human health hazards due to short-term climatic events. To achieve this objective, this research work lies in the depth and breadth of four primary components of each EWS: data collection approaches, platform development, and digital visualisation and decision-maker engagement leveraging social media and mobile apps.

Section 2 will initially delve into the research design and offer a concise bibliometric analysis. Notably, the nature of large-scale EWS, encompassing international and national platforms, differs significantly from local efforts. To maintain clarity, these two groups have organised into two sections to maintain a unique perspective on the challenges and opportunities associated with EWS deployment across various levels. Section 3 provides an overview of national and international EWS applied for detecting climate-related disease outbreaks, and in Section 4, cutting-edge forecasting platforms at the local level are explored. Moreover, Section 5 is dedicated exclusively to the application of digital visualisation technologies in EWS, considering recent advancements, novel applications and heightened real case study focus on this aspect. Finally, in Section 6, current challenges and offer insights into future perspectives are elucidated. This section offers fresh insights into the evolving landscape of EWS, especially in the context of climate-related disease outbreaks. This section is encapsulated within the concluding remarks at the end of the study.

2. Research design

The present study followed the guidelines recommended by Ref. [28] to select appropriate research works from the Scopus search engine. A set of six search and screen strategies (S1–S6) were used and are presented in Fig. 4. The search results started with identifying publications on climatic hazards related to disease outbreaks and EWS, resulting in 1577 papers in S1. The search was then narrowed down by focusing on various types of WRCH, resulting in 259 publications in S2. The search was further restricted to the last decade, i.e., after 2012, for English language journal papers only, resulting in 73 articles in S3 to provide more advanced and recent research studies. The selected papers were then classified into three categories: 27 papers for data collection (S4), 31 papers for developed platforms (S5), and 39 papers for digital visualisation (S6). These research works are then reviewed and the finding are provided into the three categories of (1) large-scale EWS i.e., national or international platforms, (2) local DTI applied for developing EWS, and (3) role of digital visualisation in EWS.

2.1. *Brief bibliometric analysis on the selected research works*

Based on the selected 73 papers in stage 3 of research design i.e. S4 in Fig. 4, bibliometric analysis was conducted using the VOSviewer software. The analysis was based on the co-occurrence of key terms in the titles and abstracts of the papers, and the counting method used was full counting. The density of keywords is illustrated in Fig. 5a, which shows that although the focus area of all selected papers is flooding, there is only one set of strongly connected studies surrounded by many non-connected studies.

Further analysis of this cluster revealed 5 main subclusters as shown in Fig. 5b. The purple cluster focuses on the application of the "Internet of things" supported by "big data" and "Machine learning". The red cluster focuses more on the "Early warning system" and associated different attempts, including modelling, using sensors, and integration of communication platforms. The green cluster is mainly represented by "virtual reality" (VR) connected to "flood management" through mainly "disaster awareness", simulation of and "flood submergence". The yellow cluster illustrates "augmented reality" (AR) with a focus on providing immersive 3D experiences for communication. Finally, the blue cluster demonstrates the general application of 3D visualisation, especially "mixed reality" in "flood risk management/assessment".

Fig. 5c shows that hot topics have shifted from the application of Geographic Information Systems (GIS) in 3D visualisation, field surveying in AR, modelling of flood submergence by VR, and using real-time monitoring kit in EWS and events to the internet of things (IoT), smart devices, and risk perception. Fig. 5c shows that hot topics have shifted from the application of GIS in 3D visualisation, field surveying in AR, modelling of flood submergence by VR, and using real time monitoring kit in EWS and events to IoT, smart devices, and risk perception.

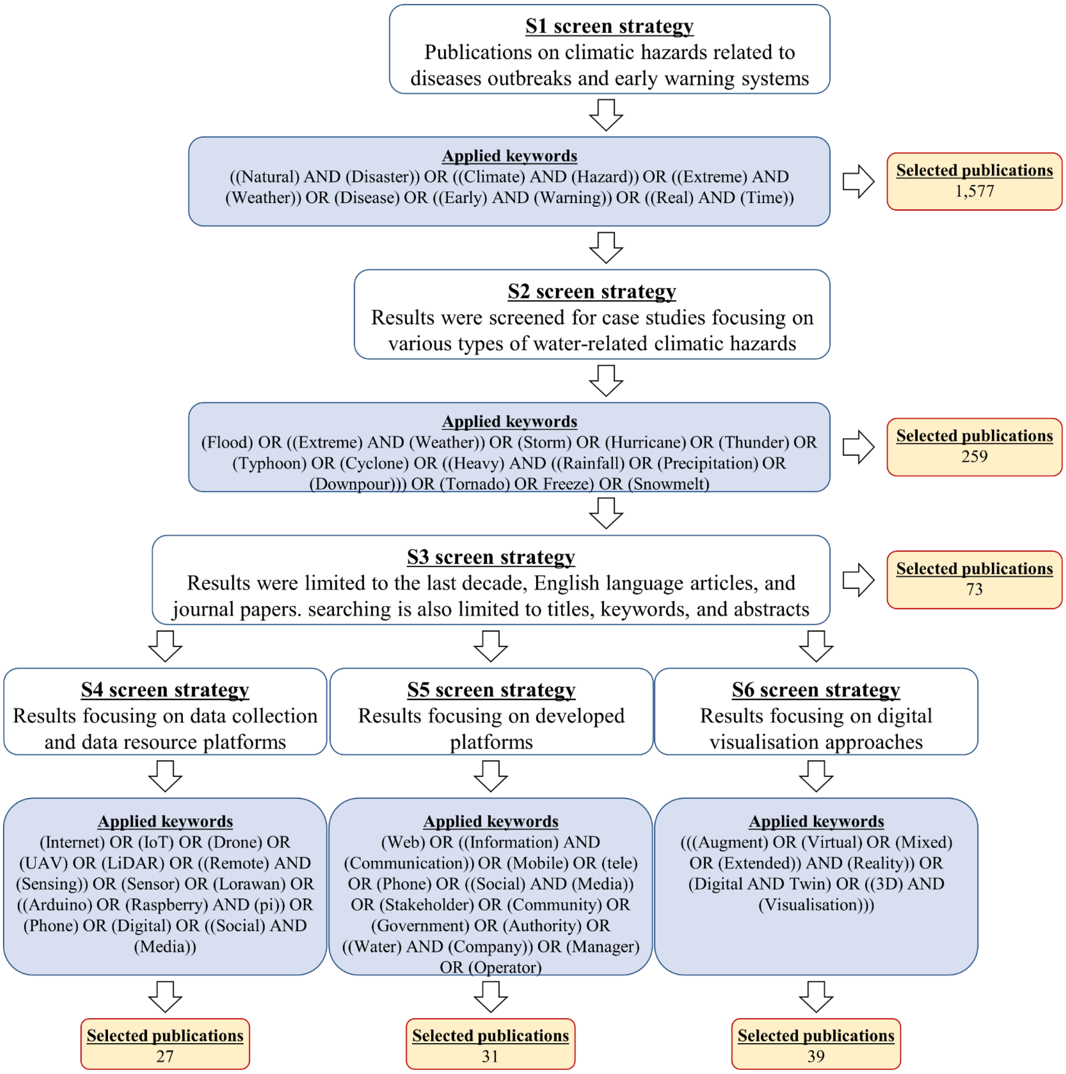

Fig. 4. Flowchart of screen strategies for selecting research works used in this study.

3. National and international early warning platforms for disease outbreaks

Climate change affects wider areas and multiple climatic events simultaneously. Therefore, large-scale systems covering multiple countries can better describe the scenario of novel technologies' applications in EWS for tackling extreme climatic events associated with diseases [29]. High-coverage EWS typically uses information provided by research projects, institutes, organisations, and government agencies and returns it in the form of alerts, reports, open-source databases, satellite imagery, tools, and modelling services [30]. The entire process involves the use of digital resources at various stages, including identification of hazards and risk areas, monitoring systems, data analysis and processing, modelling tools, information distribution, and EWS operation [31].

Table 1 illustrates various EWS that use digital technologies to detect and warn about natural hazards related to water and their potential to increase the risk of disease outbreaks. Some of these systems, such as "Climate Information Tool for Agriculture" and "Digital Earth Africa", provide predictions for securing food production but are solely focused on the African continent. Other EWS, such as the "Global Flood Awareness System", provide 30-day forecasts for riverine floods at a global scale. However, the E3 Network, which uses climatic information for disease prevention, is limited to the European Union and does not cover areas with high mortality rates due to vector-borne diseases such as South America, Africa and South Asia.

The "Early Warning, Alert and Response System" is a unique EWS that focuses on disease detection after a natural disaster or conflict, using tools and devices for disease data collection, storage and reporting to activate a response as early as possible. It is important to note that these digital technologies and EWS need to be connected to a risk-based approach and decision-making system supported by multi-criteria decision analysis tools for informed decision-making at the appropriate time. A decision support system can encapsulate this approach through several modules, including a database of potential intervention options/plausible scenarios [37,38].

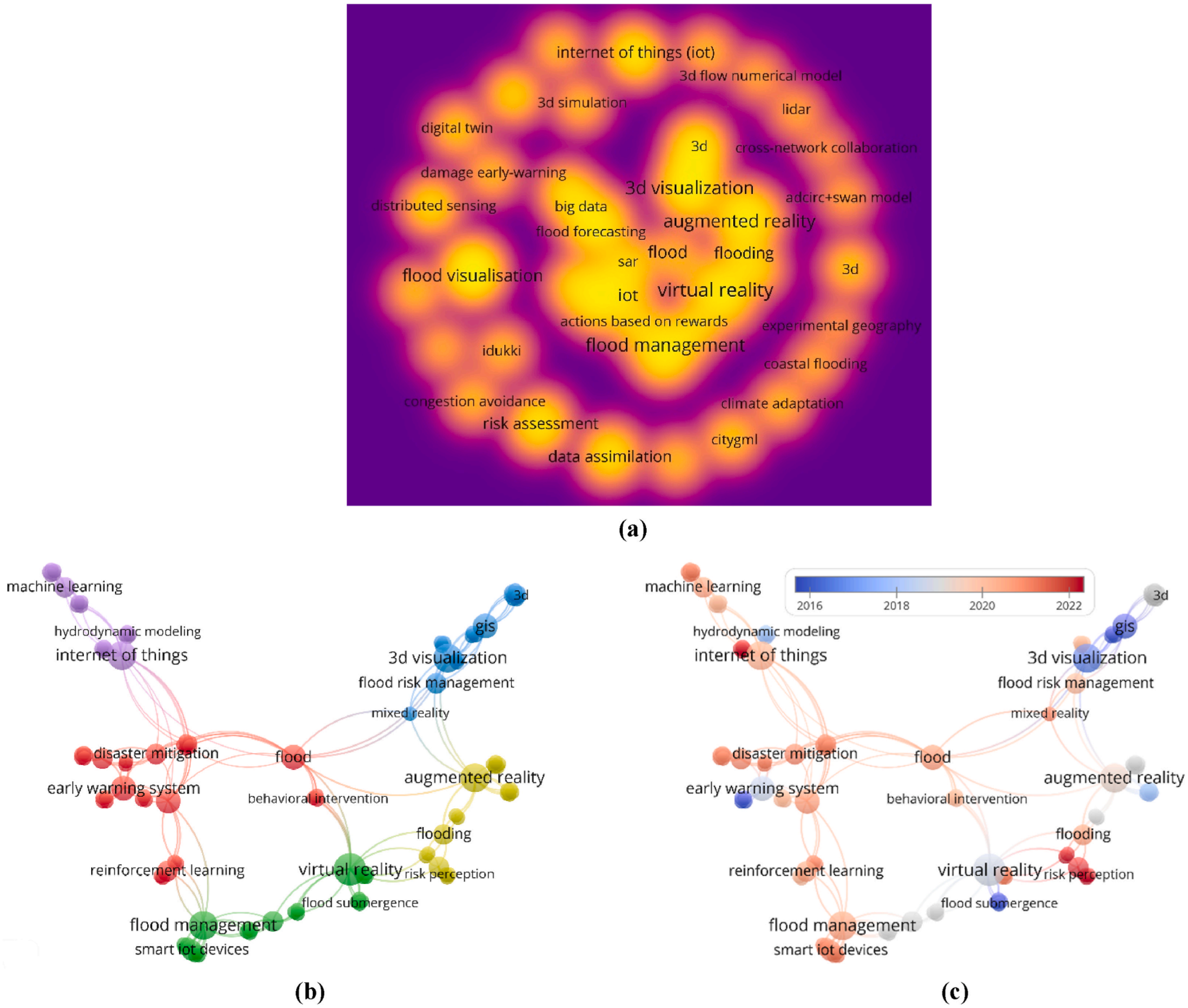

Fig. 5. Bibliometric analysis for the selected papers based on a) density of all keywords, b) cluster of connected keywords, c) timeline of connected keywords.

Numerous EWS have been developed and operated on national scales so far, primarily under the purview of meteorological offices and environmental agencies [39,40]. These entities have placed a significant emphasis on forecasting extreme weather events, enhancing public awareness, optimising evacuation routes, and implementing various risk management strategies [18,41]. However, these platforms have predominantly treated disease outbreaks as collateral effects of disaster management, rather than dedicating focused efforts to establish EWS specifically for disease outbreaks [24].

In contrast, the development and management of EWS with the explicit goal of addressing disease outbreaks have been largely undertaken by operational health agencies, with the overarching aim of fortifying disease control measures [26,42]. Nevertheless, it remains apparent that the seamless integration of these two distinct systems calls for a more comprehensive vision and heightened collaboration among various governmental agencies and departments. Such collaborative efforts are essential for formulating robust plans aimed at preparing for, containing, and mitigating the severity of disease outbreaks closely related to climate and environmental factors [43,44].

4. Local early warning systems for disaster forecasting

The differences between EWS are not only restricted to their coverage or objectives but are also influenced by the various digital tools and devices employed to achieve their goals. EWS climatic prediction capabilities are typically improved by using geospatial data, satellite observations, remote sensing, and advanced modelling tools [2]. Meanwhile, disease detection and monitoring tasks are aided by mobile phone technologies, data hubs, social media platforms, and alternative energy sources. The broader range of technologies used in EWS is further discussed in this section.

It is important to note that while all the selected research works discuss the impact of recent advancements on preventing disease outbreaks, they primarily focus on developing EWS for WRCH, which indirectly can contribute to disease outbreak management. In

Table 1
National and international EWS using digital technologies for the prediction or detection of disease outbreaks.

System	Year	Implemented /Funded by	Description	Features	References
EWARS[a]	2017	WHO[b]	Kit designed to help improve the detection of disease outbreaks during emergencies	- Consists of mobile phones/laptops/datahub to collect, report and manage infectious disease data. - Supports up to 50 permanent or mobile clinics with the potential to help up to 0.5 million people. - Tested successfully for mitigating and predicting dengue outbreaks in Brazil, Malaysia, and Mexico - Not open access software and mostly used for disease detection and not for disease prevention	[32]
GloFAS[c]	2018	ECC-EMS[d]	Satellite-based near real-time monitoring and forecasting of flood events around the globe forecast daily flooding up to 30 days in advance	- Combines medium-range meteorological readings and spatially distributed hydrological rainfall-runoff model. - Sends out detailed bulletins information including the predicted landfall location and areas at risk of severe flooding with a level of certainty up to 5 days. - Limited scope to rivers and no real-time forecast for flash flood risk or coastal flooding areas	[33]
CLIMTAG[e]	2018	ECMWF[f]	Web-based tool using the C3S[g] data collected from weather stations and satellites to provide historical and future relevant climatic indicators	- Provides indicators with 1 km resolution displayed on a country-wide map and graphs. - Used by farmers and decision-makers to assess the severity of climate changes on farming, ensuring adequate resilience measures and strategies are in place to secure crop production and tackle food insecurity. - Aimed to expand to over 20 countries in Africa. - Only provides climate information only for Malawi, Mozambique and Zambia.	[34]
Digital Earth Africa	2020	US-based Helmsley Charitable Trust and the Australian Government	Ambitious project setup to help improve the lives of people across Africa through satellite observations specific to the African continent.	- Provides accessible, reliable and timely data regarding changes in the continent's environmental conditions for stakeholders. - Used to aid decision-making on flooding, drought, soil and coastal erosion, agriculture, forest cover, land use and land cover change, water availability/quality and changes to human settlements. - Dedicated solely to the African continent	[35]
E3 Network[h]	2022	ECDC[i]	Timely access to data on eco-climatic determinants, vector distribution, and infectious disease incidence is gathered from various sources	- Includes data repository, geoportal for data visualisation, extraction, and dissemination, and online tools for analysing environmental and climatic disease drivers. - Obtains data through exchanges and scientific collaborations across geographical and political boundaries in the European Community between member states, researchers, ECDC experts, and other authorised users, with a particular focus on climatic change adaptation, landscape epidemiology, and emerging disease threats. - Involves a wide range of technologies including GIS, satellites, remote sensing, and modelling tools. - Difficulties in the attribution of emerging infectious diseases to specific climate events	[36]

[a] Early Warning, Alert and Response System.
[b] World Health Organization.
[c] The Global Flood Awareness System.
[d] European Commission's Copernicus Emergency Management Service.
[e] CLimate InforMation Tool for Agriculture.
[f] European Centre for Medium-Range Weather Forecasts.
[g] Climate Change Service.
[h] The European Environment and Epidemiology.
[i] European Centre for Disease Prevention and Control.

alignment with the primary focus of these research works, this study also highlights these advancements accordingly. However, the potential of the direct application of these technologies to Disease-based EWS are explored to consider how these technological innovations can directly enhance the effectiveness of EWS dedicated to disease outbreak monitoring and response.

4.1. Critical analysis on cutting-edge digital technologies

Digital technologies are rapidly advancing, providing increasingly sophisticated tools for disaster prediction, prevention, and mitigation. Commonly used digital technologies in these processes include satellites, unmanned aerial vehicles, drones, aircraft, helicraft, and airship data collection [19,45]. Additionally, technologies such as radio frequency and electric-conductive sensors, stationary surveillance cameras, ultrasonic and infrared sensors, visual cameras, capacitive/conductivity-based sensors, radar and LiDAR, pressure sensors, and street ultrasonic sensors are used as remote-sensing platforms [46]. These technologies primarily concentrate on response activities, such as detecting the expansion of floods in urban areas that could potentially become breeding grounds for insects or parasites [47]. They also play a crucial role in post-disaster recovery efforts by assessing the aftermath of flooding, which includes evaluating soil and water contamination, addressing hygiene concerns, and ensuring access to clean water [48,49].

As indicated in Table 2, smart sensors equipped with ultrasound, IoT, and LiDAR technology represent some of the most extensively applied digital tools for real-time data acquisition [50]; Paul et al., 2020). These technologies boast a wide array of applications, including: (1) collecting data on polluted catchment areas to assess their susceptibility to potential disease outbreaks, (2) providing critical flow for real-time modelling of damage to treatment facilities or hospitals in the event of disasters, (3) detecting high-risk areas for effective disease impact management and mitigation strategies, and (4) utilising IoT-controlled devices like gates, valves, and pumps to redirect water levels, thereby exerting control over ongoing disease outbreaks [51,52,53]. Smart sensors can also play a crucial role in gathering data on soil moisture, land movement, and rainfall intensity. This data is invaluable for identifying regions susceptible to slope failure, landslides, and road damage during severe weather conditions. Moreover, this information can help pinpoint potential areas for disease proliferation and serve as pivotal points for disease outbreaks [54].

Table 2
Cutting-edge digital technologies used for in early warning systems.

Focus area				Reference
Approach/Digital technologies	Modelling	Application	Case study	
Social media				
X (former Twitter)	Geocoding and classification	Hurricane lead time for management	USA	[55]
X (former Twitter)and YouTube	Data mining	Search and rescue	–	[52]
X (former Twitter)and API based data source	Data mining	Social geodata of flooding	UK	[56]
X (former Twitter)integrated with Google Vision	LSTM	Dynamic at-risk flood area	USA	[57]
X (former Twitter)	Data mining	Hurricane-induced infrastructure disruption	USA	[58]
X (former Twitter)	LSTM	Traffic demand during a hurricane evacuation	USA	[59]
Mobile phone apps				
Email and SMS	INFLUX platform	Flood management	France	[60]
IoT based remote sensing				
Water flow sensor	Data mining	Smart flood management	–	[61]
Water flow, water level, rain and humidity sensors	CNN	Flood hazard detection	–	[62]
Ultrasonic water level sensor	RNN	flood water control	USA	[51]
Water flow sensor	DSS	Flood risk level determination	–	[63]
Water flow sensor	SWMM	Real-time heavy rainfall forecasting	–	[64]
Water level sensor	Real-time ECOMSNET	Decision-supporting flooding information	–	[52]
Soil moisture, rainfall, and tiltmeter sensors	Algorithm-based CTRL-T	Providing landslide early warning	India	[65]
Ultrasonic water level sensor	–	GSM and Bluetooth mobile based flood warning	–	[66]
Sensors and mobile phone network	DSS	Drones, aircraft, airships, and helikites for flood warning	–	[67]
Rainfall, temperature, humidity, soil temperature, soil moisture and tiltmeter sensors	Real-time monitoring	Indicating mass movement of landsides	–	[54]
Water flow sensor	RNN	Flash flood risk management	India	[68]
Tilt, rain gauge, water level and strain sensors	–	Slope instability monitoring system	Japan	[69]
Water level and electrical conductivity sensor	–	Urban stormwater networks	–	[70]
Water flow sensor	RNN	Water flow forecasting	China	[50]
Water flow sensor	–	Rapid failure assessment	USA	[71]
Ultrasonic water level sensor	–	Flood profile data	USA	[72]
Others				
LoRaWAN and LiDAR radar remote sensing	Inundation predictions	Regional resilience monitoring network	USA	[73]
Satellite and ground real-time data	ADCIRC and SWAN	Web-based interface for data visualisation	USA	[74]
Lidar-based water level sensors	–	Providing long-distance measurement	–	[47]
IoD-based network	Message forwarding algorithm	Smooth message dissemination	–	[75]

ADCIRC Advanced CIRCulation model for oceanic, coastal and estuarine waters.
API: Application programming interface.
CNN: Convolutional Neural Network.
CTRL-T: Rainfall-induced Landslides Tool.
DSS: Decision Support System.
ECOMNET: Edge COMputing-based Sensory NETwork.
IOD: Internet of Drones.
IoT: Internet of Things.
LiDAR: Light Detection And Ranging.
LoRaWAN: Long Range Wide Area Network.
LSTM: Long Short-Term Memory.
RNN: Recurrent Neural Network.
SWAN: Smart Water Networks Forum.

Although some digital innovations have only recently become available for use in data collection and dissemination, researchers and developers can now easily access application programming interfaces (APIs) to obtain data (e.g., see Ref. [76]. In addition, low-cost portable sensors are now accessible to supplement data collection from online databases and real-time transmission of collected data is easily possible through digital technologies such as LoRaWan, ad-hoc LAN networks, and Wi-Fi technologies [63,73]. Therefore, it seems that, the next step in this context is to focus on developing affordable sensors capable of measuring the growth potential of diseases, including real-time bacteria detection, virus recognition, and parasite detection [24].

Finally, mobile phones and social media platforms have emerged as increasingly vital tools for not only detecting, addressing, and warning about disease outbreaks but also for comprehensively managing them when triggered by severe weather events [55,57]. These platforms, such as X (former Twitter) and YouTube, have been proven remarkably effective in rapidly gathering information about flooded areas, disruptions in transportation routes, infrastructure damage, individuals in distress, and the initial signs of disease outbreaks from a wide array of sources [58,59]. This multifaceted approach allows for a more nuanced and timely response to disease outbreaks triggered by extreme weather conditions, helping curb their spread and minimise their impact on vulnerable populations [52].

Users can post observations, photos, and videos of weather-related incidents. This crowdsourced data can provide valuable insights into the extent of damage and the areas most affected and be used for disease-based EWS [56]. Also, public sentiment and conversations related to weather events, health concerns, and affected population can be tracked by EWS. Sudden spikes in discussions about illness symptoms or clusters of related posts can trigger further investigation and response from health authorities [57]. Consequently, the integration of mobile technology and social media in disaster management not only offers enhanced situational awareness but also opens up new avenues for proactive interventions in disease outbreaks during extreme weather events.

4.2. Overview of recent trends on cutting-edge digital technologies

Fig. 6 illustrates the overview of latest trends in cutting-edge digital innovation, in comparison to the well-established digital technologies that are used for climatic hazards EWS and consequently disease outbreak prevention. While portable and static rainfall, water level, and water flow stations are now being used to provide EWS with real-time and reliable sources of data, local sensors such as IoT, IoD, and Lidar sensors are being developed to provide more accurate data, albeit with less coverage [77]. Social media and mobile phones are also adding more social and qualitative data, transforming the EWS from a purely engineering perspective to a more comprehensive one. Furthermore, proposed data-driven, physically-based, conceptual or dynamic models are being advanced by the concept of real-time online forecasting. Traditionally, more technical outputs such as damage cost analysis, forecasted water depth, inundation or susceptibility maps, and reliability and resiliency maps were generated for experts. However, the new trend is to provide web-based interfaces or information communication platforms to engage stakeholders in more interactive human interfaces.

4.3. Statistical analysis on cutting-edge digital technologies

A total of seven technologies are recognised here that go beyond the EWS, as shown in Fig. 7a. These include IoT-based sensors, social media, APIs, mobile phones, online web-based platforms, LAN services, and IoD-based sensors. Among all the new technologies,

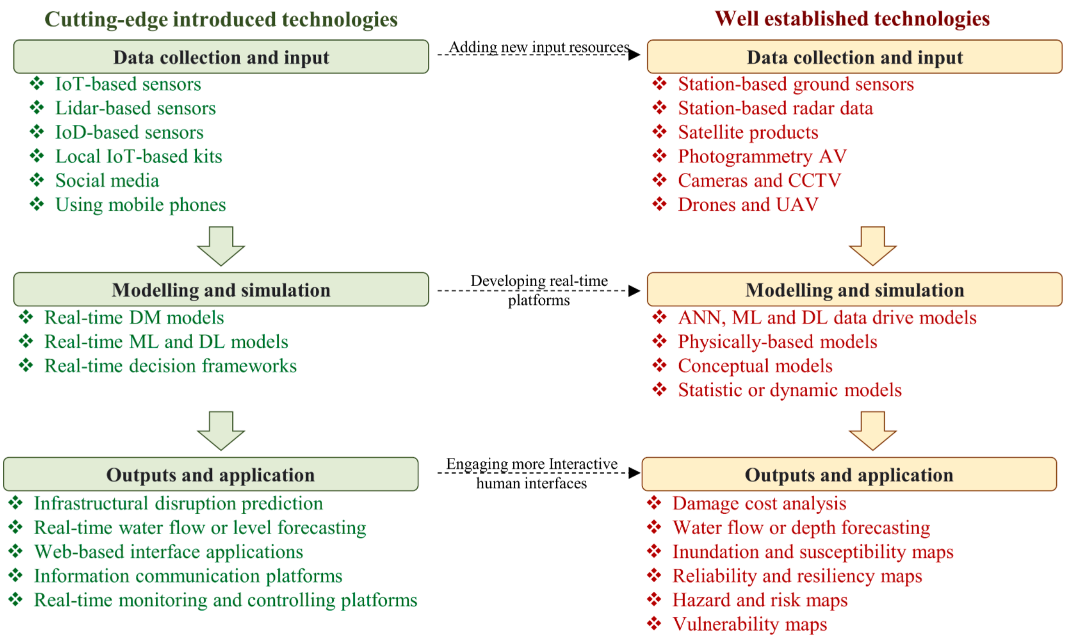

Fig. 6. Overview of new trends of cutting-edge digital innovation in comparison with well-established digital technologies used for EWS.

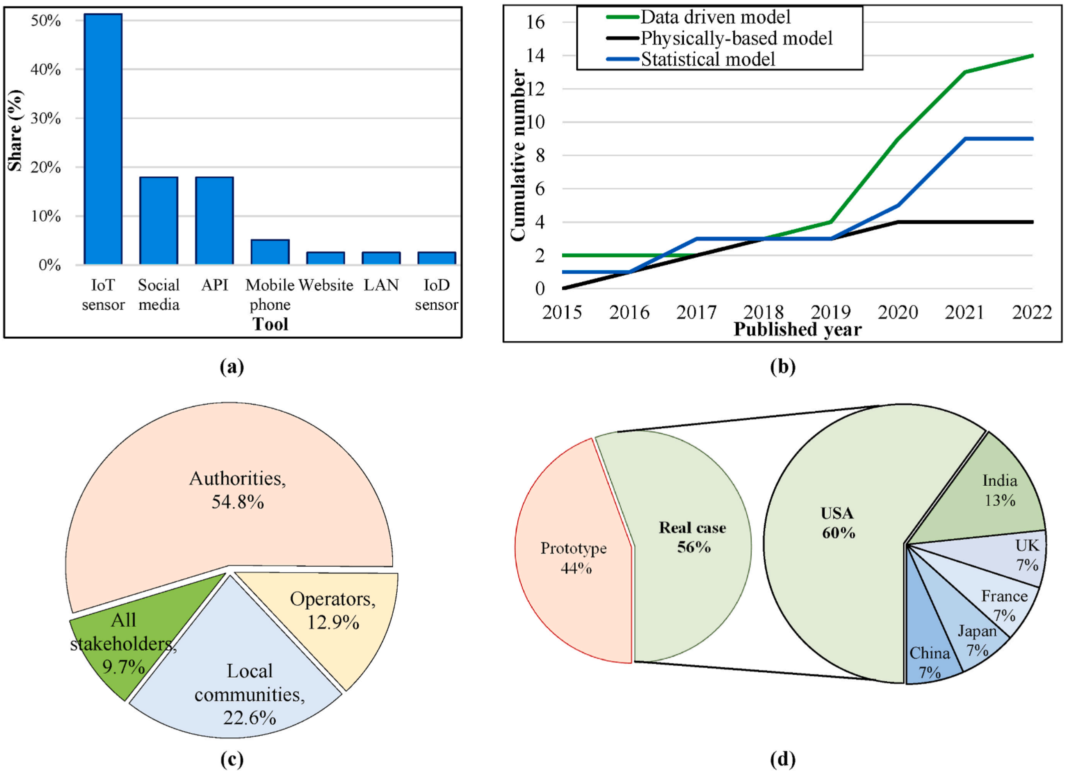

Fig. 7. Dashboard of recent applications of digital technologies on local EWS (out of 27 studies): (a) share of technologies, (b) number of research publications based on applied models, (c) target audiences, and (d) geographical distribution.

IoT sensors are the most extensively researched, followed by social media and using APIs which are becoming increasingly popular. The information collected by these sensors is commonly used for the development of physical or data-driven models (Fig. 7b), which help to identify and assess the susceptibility of risk areas to extreme climatic events [78]. While data-driven models have become more popular in recent years, simple statistical models used mainly in web-based real-time platforms have also grown in popularity [79,80].

These models share information with the public or targeted audiences, especially authorities, operators, and local communities. While they mainly focus on authorities (See Fig. 7c) such as decision makers, policy makers or in-field managers, only around 20 % of total selected papers include local communities. This is especially significant because frontline communities are typically the ones who experience the initial impact of extreme weather or disease outbreaks events and frequently step up as the first responders during emergencies. Consequently, they possess invaluable local knowledge about their environment [47]. Similarly, other stakeholders such as businesses, hospitals, and schools may have specific needs and concerns related to hazards that should be addressed in the EWS. By considering the needs of all stakeholders, the system can help ensure that everyone is adequately prepared and able to respond effectively to hazards, reducing the overall impact on the community [81,82].

While the implementation of cutting-edge technologies demonstrates recent progress, as indicated in Fig. 7d, it is noteworthy that only half of the total research works have been tested in real-world case studies, reflecting the early stages of commercialisation for these technologies. Furthermore, when examining the geographical distribution of selected studies, it becomes apparent that a few countries, with the USA and India leadership, have heavily pursued research in this context. This leaves room for more efforts in other regions that are equally impacted, such as Middle Eastern, North African, and Southeast Asian countries [3].

5. Application of digital visualisation in early warning systems

Numerous research studies have leveraged digital visualisation techniques to forecast and mitigate the impact of extreme events or WRCH. These techniques have been employed for tasks such as damage assessment, evacuation route planning, and inundation simulation, as evidenced by works such as those by Refs. [15,83]. Furthermore, applications of these technologies in the context of disease outbreaks are documented within the field of medical science, as exemplified by Ref. [84]. However, it seems that there is a relative scarcity of studies specifically addressing the intersection of disease outbreaks and climate-related hazards, a gap that will be explored in the subsequent discussion.

5.1. Critical analysis on cutting-edge digital visualisation technologies

In recent years, VR, AR, and digital twin (DT) have gained significant attention as innovative digital technologies for water-related climate hazard management and understanding hazard behaviour and the roles of victims. In the context of disease outbreaks, these technologies serve two primary purposes: (1) 3D visualisation of hazards and associated disease outbreaks, and (2) increasing interactive awareness among relevant stakeholders. As shown in Table 3, VR is widely used to model pluvial, fluvial, and dam-breaking floods by creating a simulated 3D environment that allows users to explore and interact with virtual surroundings [85]. This information is then presented as potential areas susceptible to the spread of infections or vulnerabilities in water, food, wastewater, or hygiene infrastructure [86].

There are two methods of implementing VR for flood risk management. The first method involves creating a game environment that allows users, either through a computer or by wearing a special device, to move around the simulated area and view flood and impact of flood-related disease outbreaks, identify potential locations where waterborne diseases can spread, contamination of food and water sources can occur, wastewater systems may fail, and hygiene infrastructures compromised ([39] [107].

The second method involves developing software to investigate and analyse flood-prone and identify health high-risk areas using various tools such as digital terrain models, LiDAR, GIS databases, and unmanned aerial or sea vehicles [92,106]. This is followed by a three-dimensional visualisation of flood modelling results to pinpoint areas where flood waters may encounter water sources, such as rivers, lakes, or reservoirs, potentially leading to contamination which can be used for EWS [89,102]. Also, these simulations can be used for tracing the vectors, their distribution around the world, prevent transmission of diseases, and areas where victims were affected [108].

AR technology, which integrates digital content with the real-world environment through sensory stimuli such as sound and visuals, has recently been applied to flood visualisation, as outlined in Table 3. The main application of this technology has been in the development of mobile apps that allow users to assess flood risks as context of community-based EWS [83]. AR can overlay relevant data

Table 3
Recent advances in applied digital visualisation used for EWS.

Applied technologies/Application	Case study	Reference
VR technologies		
Virtual flood experiment integrating cellular automata and dynamic observations	China	[87]
2D hydraulic simulations within a 3D virtual reality environment	Italy	[88]
3D hydrodynamic simulation of flooding based on the virtual presentation of UAV and USV data	Brazil	[89]
Creating realistic 3D gaming environment	USA	[90]
Risk level, the affected area, and critical locations by IVR flood environment presentation	China	[91]
Dynamic visual simulation and decision support system for flood risk management	China	[92]
Testing and measuring flood-related intervention behaviours for early evacuation	Japan	[85]
Offering games to engage the public with flood projects	UK	[93]
Dynamic 3D flood risk level map	China	[94]
High resolution of the VR flood scene	China	[39]
IVR technology to examine stimulated people	Netherlands	[95]
IVR technology to assess public perception and response to flood risk area	USA	[86]
IVR and multi-element warning and web-based forecast database	China	[96]
AR technologies		
Smartphone application to engage the public with local flood zones and potential flood levels	UK	[97]
Client-server smartphone application to reach the most critical areas	Italy	[98]
DT technologies		
"Pipedream" real-time software integrating DT of the urban water system, remote sensors and online modelling for rapid flood forecasting	USA	[99]
Providing dynamic EWS based on DT for UDS flood risk levels determination	Sweden	[100]
Hybrid technologies		
VGE simulation of flood routing integrated with DTM, and 3D GIS.	China	[101]
Dynamic flood web-based GIS visualisation	USA	[102]
Mixed reality smartphone application for in-situ flood geometry visualisation	UK	[103]
3D representations of flood inundation integrated with LiDAR, airborne data, and VR and AR as mixed reality	Italy	[104]
3D flood visualisation by using VR and AR, DEM, and GIS	Canada	[105]
Creating rapid spatial analyses of flooded areas, and estimating affected and vulnerable populations to allocate required resources such as shelters and portable hospitals	Taiwan	[106]

AR: Augmented Reality.
DEM: Digital Elevation Model.
DTM: Digital Terrain Model.
EWL: Extreme Weather Layer.
GIS: Geographic Information System.
IVR: Immersive Virtual Reality.
LiDAR: Light Detection And Ranging.
UAV: Unmanned Aerial Vehicle.
UDS: Urban Drainage Systems.
USV: Unmanned Sea Vehicle.
VGE: Virtual Geographic Environment.

and information onto the real-world environment, making complex disease-related data more accessible to users. For example, AR can display disease transmission models, infection hotspots, or population health data on a user's field of view, allowing for immediate comprehension of the situation [97]. It also can integrate geospatial data, such as GIS information, onto the user's surroundings. This allows for the visualisation of disease outbreak locations, containment zones, and affected areas directly on a map in real-time [98]. AR can also assist with contact tracing efforts or remote collaboration by providing users with visual cues about their proximity to individuals who may have been exposed to a disease. This can help individuals take necessary precautions and inform public health authorities of potential transmission chains [103].

Finally, DT technology is relatively new but promising tool for flood risk communication that are become popular recently in the context of planning and real-time management of disaster [107]. A DT system can be thought of as a complex real-time digital system that employs numerous sensors, healthcare data, and epidemiological data to provide users with information about the system's current state and potential risks and holistic view of the disease landscape [99]. Furthermore, they can provide real-time monitoring and prediction for tracking disease spread and contact tracing, by taking into account factors such as population density, mobility patterns, and climate conditions [100].

While the application of these cutting-edge technologies holds promise for enhancing EWS, they often encounter significant challenges. These challenges primarily revolve around issues of data quality and availability, especially in less-developed regions [106]. Furthermore, the handling of sensitive healthcare and epidemiological data within digital twins necessitates robust data privacy and security measures, which can become complex when sharing data among multiple stakeholders (Santis et al., 2018). Lastly, integrating human behaviour and decision-making into these technologies can be particularly intricate, primarily due to the inherent difficulty in accurately simulating how individuals respond to public health measures or vaccination campaigns [102].

5.2. Statistical analysis on cutting-edge digital visualisation technologies

According to Fig. 8a, VR technology has mainly targeted authorities (47 %) by enhancing health risk communication, 27 % of research works have focused on engaging local communities by organising workshops and introducing the nature of the flood or potential contacted disease. In stakeholders' perspective, Fig. 8b shows that VR technologies have been widely applied for all target audiences (54 %, 50 %, and 67 % of total research work for authorities, local communities, or both, respectively). However, AR technologies have mainly targeted local communities, whereas DT technologies have only targeted authorities due to their virtual representation of interactions within the system. Therefore, it seems that feasibility and effectiveness of using DT technologies for local communities still require more attention. Comparing Figs. 8b–7, with a broader inclusion of all stakeholders (9.7 % vs 30 %), there is an improvement in engagement across stakeholders, but the primary focus of the research remains on providing effective tools for early disease outbreak warnings to authorities. The majority of research efforts continue to concentrate heavily on equipping authorities with tools for planning disease spread prevention and health safety scenarios.

In Fig. 8c, which illustrates the geographical distribution of real-world case studies, a similar trend is observed as in Fig. 7c. Cutting-edge digital visualisation techniques have been applied in a greater number of countries compared to Fig. 7 (11 vs 6). However, it still indicates that there is significant progress required to establish disease outbreak management beyond the EWS. Moreover, the data shows that China places more emphasis on digital visualisation compared to the establishment of EWS, as evidenced by the substantial 60 % share of the USA in Fig. 7d.

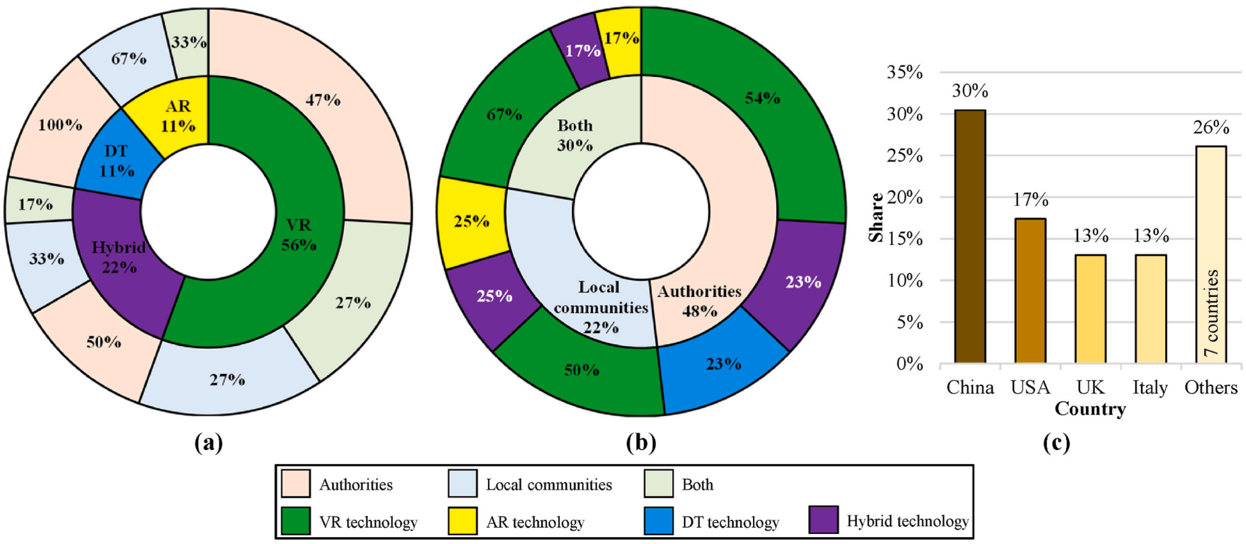

Fig. 8. Dashboard recently developed digital visualisation platforms: (a) applied technologies, (b) target audience, (c) geographical distribution (out of 23 studies).

6. Study limitations and future work

This study aims to encompass relevant research works. However, it is important to acknowledge that new discoveries and developments are continuously emerging. The study's scope is limited to published journal or conference papers that focus on prototypes or practical applications. Meanwhile, numerous recent advancements are already being put into practice at an industrial level by municipalities, water companies, and regional or national agencies. These initiatives are often protected by patents or lack of public accessibility, posing challenges in tracking or accessing the specific information needed for extraction.

As previously mentioned, while selected studies mention disease outbreaks as an objective of their research for developing EWS, disease-based EWS in the context of WRCH are rarely documented as the primary research focus. Therefore, the review of direct attempts in this area was quite challenging. This study strives to shed light on the disease outbreak aspect of these research works, and in doing so, it highlights a notable gap in disease based EWS that could facilitate the integration of information on extreme events and disease outbreaks.

Hence, it is recommended that more attention be directed towards health risk based EWS systems that leverage climatic information to predict and prevent disease outbreaks. Additionally, the exploration of 3D visualisation applications for enhancing water-related disaster awareness, demonstrating operational tasks, identifying high-risk areas for health, and simulating the development of events should be prioritised. Furthermore, there is a pressing need for further research into the evaluating and enhancing the reliability and accuracy of the technologies underpinning EWS. These attributes are foundational to the overall efficacy of EWS, exerting a profound influence on their capacity to safeguard lives and facilitate effective disaster management.

7. Conclusions

This research undertook a critical analysis of recent publications that cantered on digital innovations applied within disease-based EWS and the management of disease outbreaks induced by WRCH, consequently posing threats to human health safety. The study's concluding key findings are as follows:

- Currently a few Large-scale EWS applying geo-spatial data, satellite observations, remote sensing, and advanced modelling tools have been operated to enhance the disease outbreaks prediction. However, these platforms do not encompass all countries, particularly in cases involving disease outbreaks and multi-country spread. Given the substantial capital and operational expenses associated with these platforms, there is a pressing need for increased collaboration between multi-international agencies and governments to expand their coverage.
- Mobile phone technologies, data hubs, and social media platforms play a crucial role in monitoring and detecting affected areas and facilitating the transmission of warning messages. Nevertheless, local EWS must include a process in which all stakeholders, especially local communities situated on the front lines of human health safety, are actively engaged.
- VR, AR, and DTI have garnered significant attention as innovative digital tools for 3D visualisation of hazards. They enhance interactive awareness among relevant stakeholders regarding potential disease outbreak hotspots and contribute to effective management of disease outbreaks to ensure human health safety. However, there remains a substantial gap in the integration of these technologies into disease based EWS used for tracking WRCH.
- While emerging trends in disease based EWS within the context of WRCH are described in the literature, the practical application of these technologies is still in its nascent stages. Only a few of countries have made intensive efforts in this context, and a greater focus on certain regions, especially those located in the Middle East and Southeast Asia, due to their heightened vulnerability to water-related natural disasters, still require more attention.

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.

References

[1] R. Kusumastuti, A. Arviansyah, N. Nurmala, S. Wibowo, Knowledge management and natural disaster preparedness: a systematic literature review and a case study of East Lombok, Indonesia, Int. J. Disaster Risk Reduc. 58 (2021) 102223.
[2] F. Piadeh, K. Behzadian, A.M. Alani, A critical review of real-time modelling of flood forecasting in urban drainage systems, J. Hydrol. 607 (2022) 127476.
[3] Centre for Research on the Epidemiology of Disasters (CRED), Emergency events database [Online] Available at: www.emdat.be, 2022. (Accessed 4 January 2023).
[4] Centre for Research on the Epidemiology of Disasters (CRED), The Human Cost of Weather Related Disasters 1995-2015, 2015 [Online] Available at: undrr.org. (Accessed 4 January 2023).
[5] P. Phoobane, M. Masinde, T. Mabhaudhi, Predicting infectious diseases: a bibliometric review on Africa, Int. J. Environ. Res. Publ. Health 19 (3) (2022) 1893.
[6] Q. Liu, J. Yuan, W. Yan, W. Liang, M. Liu, J. Liu, Association of natural flood disasters with infectious diseases in 168 countries and territories from 1990 to 2019: a worldwide observational study, Global Transitions 5 (2023) 149–159.
[7] J. Leandro, C. Hotta, T. Pinto, D. Ahadzie, Expected annual probability of infection: a flood-risk approach to waterborne infectious diseases, Water Res. 219 (2022) 118561.
[8] L. Gong, S. Hou, B. Su, K. Miao, N. Zhang, W. Liao, S. Zhong, Z. Wang, L. Yang, C. Huang, Short-term Effects of Moderate and Severe Floods on Infectious Diarrheal Diseases in Anhui Province, China, vol. 675, Science of The Total Environment, 2019, pp. 420–428.

[9] C.D. Girotto, K. Behzadian, A. Musah, A.S. Chen, A. Ali, L.C. Campos, Impact of water and sanitation services on cholera outbreaks in sub-Saharan Africa, in: The Virtual Conference of AQUA≈360: Water for All - Emerging Issues and Innovations, Exeter, September, 2021 UK.
[10] C. Salvador, R. Nieto, C. Linares, J. Díaz, C.A. Alves, L. Gimeno, Drought effects on specific-cause mortality in Lisbon from 1983 to 2016: risks assessment by gender and age groups, Sci. Total Environ. 751 (2021) 142332.
[11] National health system (NHS), Glossary of NHS, 2022 [Online] Available at: healthcareers.nhs.uk. (Accessed 4 January 2023).
[12] World Health Organisation (WHO), Mental Health Atlas 2020 [Online] Available at: 2020 who.int. (Accessed 4 January 2023).
[13] N. Ogden, L. Lindsay, Effects of climate and climate change on vectors and vector-borne diseases: Ticks are different, Trends Parasitol. 32 (8) (2016) 646–656.
[14] K. Reiter, N. Knittel, G. Bachner, S. Hochrainer-Stigler, Barriers and ways forward to climate risk management against indirect effects of natural disasters: a case study on flood risk in Austria, Climate Risk Management 36 (2022) 100431.
[15] V. Bakhtiari, F. Piadeh, A. Chen, K. Behzadian, Stakeholder Analysis in the Application of Cutting-Edge Digital Visualisation Technologies for Urban Flood Risk Management: A Critical Review, Expert Systems with Applications, 2023 121426.
[16] United Nations Office for Disaster Risk Reduction (UNDRR), [Online] Available at: ndrr.org Sendai Framework for Disaster Risk Reduction 2015-2030. United Nations office of disaster risk reduction. A/CONF.224.CRP.1 (2015) 6-8. (Accessed 4 January 2023).
[17] W. Honghui, T. Xianguo, L. Yan, L. Qi, N. Donglin, M. Lingyu, Y. Jiaxin, Research of the hardware Architecture of the Geohazards monitoring and early warning system based on the IOT, Procedia Comput. Sci. 107 (2017) 111–116.
[18] R. Mukhtar, Review of national multi-hazard early warning system plan of Pakistan in context with Sendai framework for disaster risk reduction, Procedia Eng. 212 (2018) 206–213.
[19] M. Kucharczyk, C. Hugenholtz, Remote sensing of natural hazard-related disasters with small drones: global trends, biases, and research opportunities, Rem. Sens. Environ. 264 (2021) 112577.
[20] F. Piadeh, K. Behzadian, A.M. Alani, Multi-step flood forecasting in urban drainage systems using time-series data mining techniques, in: Water Efficiency Conference, West Indies, Trinidad and Tobago. Repository, 2022 uwl.ac.uk/id/eprint/9690. (Accessed 31 December 2022).
[21] S. Nadkarni, R. Prügl, Digital transformation: a review, synthesis and opportunities for future research, Management Review Quarterly 71 (2021) 233–341.
[22] K. Kitazawa, S. Hale, Social media and early warning systems for natural disasters: a case study of Typhoon Etau in Japan, Int. J. Disaster Risk Reduc. 52 (2021) 101926.
[23] O. Moraes, Proposing a metric to evaluate early warning system applicable to hydrometeorological disasters in Brazil, Int. J. Disaster Risk Reduc. 87 (2023) 103579.
[24] A. Sivaprasad, N. Beevi, T. Manojkumar, Dengue and early warning systems: a review based on social network analysis, Procedia Comput. Sci. 171 (2020) 253–262.
[25] E. Parker, J. Mo, R. Goodman, The dermatological manifestations of extreme weather events: a comprehensive review of skin disease and vulnerability, The Journal of Climate Change and Health 8 (2022) 100162.
[26] T. Alcayna, I. Fletcher, R. Gibb, L. Tremblay, S. Funk, B. Rao, R. Lowe, Climate-sensitive disease outbreaks in the aftermath of extreme climatic events: a scoping review, One Earth 5 (4) (2022) 336–350.
[27] I. Kouadio, S. Aljunid, T. Kamigaki, K. Hammad, H. Oshitani, Infectious diseases following natural disasters: prevention and control measures, Expert Rev. Anti-infect. Ther. 10 (1) (2012) 95–104.
[28] D. Moher, A. Liberati, J. Tetzlaff, D. Altman, Preferred reporting items for systematic reviews and Meta-Analyses: the PRISMA Statement, PLoS Med. 6 (7) (2009) e1000097.
[29] M. Kuller, K. Schoenholzer, J. Lienert, Creating effective flood warnings: a framework from a critical review, J. Hydrol. 602 (2021) 126708.
[30] E. Theron, C. Bills, E. Hynes, W. Stassen, C. Rublee, Climate change and emergency care in Africa: a scoping review, African Journal of Emergency Medicine 12 (2) (2022) 121–128.
[31] W. Wang, T. Zhang, T. Yao, B. An, Monitoring and early warning system of Cirenmaco glacial lake in the central Himalayas, Int. J. Disaster Risk Reduc. 73 (2022) 102914.
[32] Global Early Warning, Alert and response system (EWARS), in: EWARS Official Website, 2022 [Online] Available at: project.ewars.ws [Accessed 04/09/2022].
[33] European Commission's Copernicus Emergency Management Service (Copernicus EMS), Copernicus EMS *Official Website*, 2022 [Online] Available at: globalfloods.eu. (Accessed 4 October 2022).
[34] European Centre for Medium-Range Weather Forecasts (ECMWF), ECMWF *Official Website*, 2022 [Online] Available at: ecmwf.int. (Accessed 4 September 2022).
[35] Digital Earth Africa, Digital Earth Africa *Official Website*, 2022 [Online] Available at: digitalearthafrica.org. (Accessed 4 October 2022).
[36] European Centre for Disease Prevention and Control (ECDC), ECDC Official Website, 2022 [Online] Available at: eoportal.ecdc.europa.eu. (Accessed 4 September 2022).
[37] M. Karami, K. Behzadian, A. Ardeshir, A. Hosseinzadeh, Z. Kapelan, A multi-criteria risk-based approach for optimal planning of SuDS solutions in urban flood management, Urban Water J. 19 (10) (2022) 1066–1079.
[38] A. Ferdowsi, B. Zolghadr-Asli, S.F. Mousavi, K. Behzadian, Chapter 4 flood risk management through multi-criteria decision-making: a review, in: Multi-Criteria Decision Analysis: Multi-Criteria Decision Analysis: Case Studies in Disaster Management, CRC Press, 2022, pp. 43–54.
[39] L. Fu, J. Schwartz, A. Moy, C. Knaplund, M. Kang, K. Schnock, J. Garcia, H. Jia, P. Dykes, K. Cato, D. Albers, S. Rossetti, Development and validation of early warning score system: a systematic literature review, J. Biomed. Inf. 105 (2020) 103410.
[40] Met Office, Met Office Glossary, 2022 [Online] Available at: digital.nmla.metoffice.gov.uk. (Accessed 4 January 2023).
[41] S. Sufri, F. Dwirahmadi, D. Phung, S. Rutherford, A systematic review of community engagement (CE) in disaster early warning systems (EWSs), Progress in Disaster Science 5 (2020) 100058.
[42] D. Campbell-Lendrum, L. Manga, M. Bagavoko, J. Sommerfeld, Climate change and vector-borne disease: what are the implications for public health research and policy? Philosophical Transactions of the Royal Society B 370 (2015) 20130552.
[43] C. Pley, M. Evans, R. Lowe, H. Montgomery, S. Yacoub, Digital and technological innovation in vector-borne disease surveillance to predict, detect, and control climate-driven outbreaks, Lancet Planet. Health 5 (10) (2021) e739–e745.
[44] Z. Butt, Chapter 15 - early warning for emerging infectious disease outbreaks: digital disease surveillance for public health preparedness and response, in: Patricia Ordóñez de Pablos, Xi Zhang, Information Technologies in Healthcare Industry, Accelerating Strategic Changes for Digital Transformation in the Healthcare Industry, vol. 2, Academic Press, 2023, pp. 309–320.
[45] P. Cui, J. Peng, P. Shi, H. Tang, C. Ouyang, Q. Zou, L. Liu, C. Li, Y. Lei, Scientific challenges of research on natural hazards and disaster risk, Geography and Sustainability 2 (3) (2021) 216–223.
[46] A. Filonenko, Wahyono, D. Hernández, D. Seo, K. Jo, Real-time flood detection for video surveillance, in: IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, 2015, pp. 4082–4085.
[47] J. Paul, W. Buytaert, N. Sah, A technical evaluation of lidar-based measurement of river water levels, Water Resource Research 56 (2020) e2019WR026810.
[48] M. Mousa, X. Zhang, C. Claudel, Flash flood detection in urban cities using ultrasonic and infrared sensors, IEEE Sensor. J. 16 (19) (2016) 7204–7216.
[49] H. Moghadas, R. Mirzavand, P. Mousavi, Early detection of flood in urban catch basins using radio frequency slot line array, Measurement 134 (2019) 515–518.
[50] C. Chen, J. Jiang, Y. Zhou, N. Lv, X. Liang, S. Wan, An edge intelligence empowered flooding process prediction using Internet of things in smart city, J. Parallel Distr. Comput. 165 (2022) 66–78.
[51] A. Mullapudi, M. Lewis, C. Gruden, B. Kerkez, Deep reinforcement learning for the real-time control of stormwater systems, Adv. Water Resour. 140 (2020) 103600.
[52] T. Yang, C. Wang, S. Lin, ECOMSNet – an edge computing-based sensory network for real-time water level prediction and correction, Environ. Model. Software 131 (2020) 104771.

[53] S. Schismenos, D. Emmanouloudis, G. Stevens, S. Eslamian, Torrential and flash flood warning, in: S. Eslamian, F. Eslamian (Eds.), Flood Handbook: Impacts and Management, first ed., Imprint CRC Press, 2022, pp. 16–28.
[54] C. Prakasam, R. Aravinth, V. Kanwar, B. Nagarajan, Design and Development of Real-time landslide early warning system through low-cost soil and rainfall sensors, Mater. Today: Proc. 45 (6) (2021) 5649–5654.
[55] Y. Kryvasheyeu, H. Chen, E. Moro, P. Hentenryck, M. Cebrian, Performance of social network sensors during hurricane Sandy, PLoS One 10 (2) (2015) e0117288.
[56] J. Barker, C. Macleod, Development of a National-Scale Real-Time Twitter Data Mining Pipeline for Social Geodata on the Potential Impacts of Flooding on Communities, vol. 115, Environmental Modelling & Software, 2019, pp. 213–227.
[57] N. Donratanapat, S. Samadi, J. Vidal, S. Tabas, A national scale big data analytics pipeline to assess the potential impacts of flooding on critical infrastructures and communities, Environ. Model. Software 133 (2020) 104828.
[58] K. Roy, S. Hasan, P. Mozumder, A multilabel classification approach to identify hurricane-induced infrastructure disruptions using social media data, Comput. Aided Civ. Infrastruct. Eng. 35 (12) (2020) 1387–1402 Roy, K., Hasan, S., Mozumder P. (2020).
[59] K. Roy, S. Hasan, A. Culotta, N. Eluru, Predicting traffic demand during hurricane evacuation using Real-time data from transportation systems and social media, Transport. Res. C Emerg. Technol. 131 (2021) 103339.
[60] M. Mure-Ravaud, G. Binet, M. Bracq, J. Perarnaud, A. Fradin, X. Litrico, A Web Based Tool for Operational Real-Time Flood Forecasting Using Data Assimilation to Update Hydraulic States, vol. 84, Environmental Modelling & Software, 2016, pp. 35–49.
[61] S. Sood, R. Sandhu, K. Singla, V. Chang, IoT, big data and HPC based smart flood management framework, Sustainable Computing: Informatics and Systems 20 (2018) 102–117.
[62] M. Anbarasan, B. Muthu, B. Sivaparthipan, R. Sundarasekar, S. Kadry, S. Krishnamoorthy, D. Jackson Samuel, A. Dasel, Detection of flood disaster system based on IoT, big data and convolutional deep neural networks, Comput. Commun. 150 (2020) 150–157.
[63] N. Kumar, P. Goyal, G. Kapil, A. Agrawal, R. Ahmad Khan, Flood risk finder for IoT based mechanism using fuzzy logic, Mater. Today: Proc. (2020) 698.
[64] Y. Wang, X. Chen, L. Wang, G. Min, Effective IoT-facilitated storm surge flood modeling based on deep reinforcement learning, IEEE Internet Things J. 7 (7) (2020) 6338–6347.
[65] M. Abraham, N. Satyam, A. Rosi, B. Pradhan, S. Segoni, Usage of antecedent soil moisture for improving the performance of rainfall thresholds for landslide early warning, Catena 200 (2021) 105147.
[66] K. Chaduvula, K. Kumar, B. Markapudi, C. Jyothi, Design and Implementation of IoT based flood alert monitoring system using microcontroller 8051, Mater. Today: Proc. (2021) 48.
[67] M. Hasan, A. Rahman, A. Sedigh, U. Khasanah, A. Asyhari, H. Tao, S. Abu Bakar, Search and rescue operation in flooded areas: a survey on emerging sensor networking-enabled IoT-oriented technologies and applications, Cognit. Syst. Res. 67 (2021) 104–123.
[68] H. Rai Goyal, K. Ghanshala, S. Sharma, Flash flood risk management modelling in Indian cities using IoT based reinforcement learning, Mater. Today: Proc. 46 (20) (2021) 10533–10538.
[69] M. Sheikh, Y. Nakata, M. Shitano, M. Kaneko, Rainfall-induced unstable slope monitoring and early warning through tilt sensors, Soils Found. 61 (4) (2021) 1033–1053.
[70] B. Shi, S. Catsamas, P. Kolotelo, M. Wang, A. Lintern, D. Jovanovic, P. Bach, A. Deletic, D. McCarthy, A low-cost water depth and electrical conductivity sensor for detecting inputs into urban stormwater networks, Sensors 21 (2021) 3056.
[71] U. Gangwal, S. Dong, Critical facility accessibility rapid failure early-warning detection and redundancy mapping in urban flooding, Reliab. Eng. Syst. Saf. 224 (2022) 108555.
[72] A. Silverman, T. Brain, B. Branco, P. Challagonda, P. Choi, R. Fischman, K. Graziano, E. Hénaff, C. Mydlarz, P. Rothman, R. Toledo-Crow, Making Waves: Uses of Real-Time, Hyperlocal Flood Sensor Data for Emergency Management, Resiliency Planning, and Flood Impact Mitigation, Water Research, 2022 118648.
[73] D. Loftis, D. Forrest, S. Katragadda, K. Spencer, T. Organski, C. Nguyen, S. Rhee, StormSense: a new integrated network of IoT water level sensors in the smart cities of Hampton roads, VA, Mar. Technol. Soc. J. 52 (2018) 4031.
[74] A. Khalid, C. Ferreira, Advancing real-time flood prediction in large estuaries: iFLOOD a fully coupled surge-wave automated web-based guidance system, Environ. Model. Software 131 (2020) 104748.
[75] S. Yaqoob, A. Ullah, M. Awais, I. Katib, A. Albeshri, R. Mehmood, M. Raza, S. Islam, J. Rodrigues, Novel congestion avoidance scheme for Internet of Drones, Comput. Commun. 169 (2021) 202–210.
[76] Environment Agency (EA), EA Official Website, 2022 [Online] Available at: Environment.data.gov.uk. (Accessed 12 December 2022).
[77] C.D. Girotto, F. Piadeh, K. Behzadian, M. Zolgharni, A.S. Chen, L.C. Campos, Role of Satellite Precipitation Products in Real-Time Predictions of Urban Rainfall-Runoff by Using Machine Learning Modelling, EGU23 conference, Vienna, Austria, 2023, https://doi.org/10.5194/egusphere-egu23-10211.
[78] M. Zounemat-Kermani, E. Matta, A. Cominola, X. Xia, Q. Zhang, Q. Liang, R. Hinkelmann, Neurocomputing in surface water hydrology and hydraulics: a review of two decades retrospective, current status and future prospects, J. Hydrol. 588 (2020) 125085.
[79] F. Piadeh, K. Behzadian, A. Chen, L. Campos, Z. Kapelan, Event-based decision support algorithm for real-time flood forecasting in urban drainage systems using Machine learning modelling, Journal of Environmental Modelling and Software 167 (2023) 105772.
[80] F. Piadeh, K. Behzadian, A. Chen, L. Campos, J. Rizzuto, Real-time Flood Overflow Forecasting in Urban Drainage Systems by Using Time-Series Multi-Stacking of Data Mining Techniques, EGU23 conference, Vienna, Austria, 2023, https://doi.org/10.5194/egusphere-egu23-8574.
[81] R. Rai, M. Homberg, G. Ghimire, C. McQuistan, Cost-benefit analysis of flood early warning system in the Karnali River Basin of Nepal, Int. J. Disaster Risk Reduc. 47 (2020) 101534.
[82] F. Piadeh, M. Ahmadi, K. Behzadian, A novel planning policy framework for the recognition of responsible stakeholders in the of industrial wastewater reuse projects, Journal of Water Policy 24 (9) (2022) 1541–1558.
[83] V. Bakhtiari, F. Piadeh, K. Behzadian, Z. Kapelan, Application of Cutting-Edge Digital Visualisation Technologies for Effective Urban Flood Risk Management, Journal of Sustainable cities and Society, 2023 104958.
[84] A. Asadzadeh, T. Samad-Soltani, P. Rezaei-Hachesu, Applications of virtual and augmented reality in infectious disease epidemics with a focus on the COVID-19 outbreak, Inform. Med. Unlocked 24 (2021) 100579.
[85] T. Fujimi, K. Fujimura, Testing public interventions for flash flood evacuation through environmental and social cues: the merit of virtual reality experiments, Int. J. Disaster Risk Reduc. 50 (5) (2020) 101690.
[86] M. Simpson, L. Padilla, K. Keller, A. Klippel, Immersive storm surge flooding: scale and risk perception in virtual reality", J. Environ. Psychol. 80 (2022) 101764.
[87] Y. Li, J. Gong, Y. Song, Z. Liu, T. Ma, H. Liu, S. Shen, W. Li, Y. Yu, Design and key techniques of a collaborative virtual flood experiment that integrates cellular automata and dynamic observations, Environ. Earth Sci. 74 (10) (2015) 7059–7067.
[88] F. Macchione, P. Costabile, C. Costanzo, R. De Santis, Moving to 3-D Flood Hazard Maps for Enhancing Risk Communication, vol. 111, Environmental modelling & software, 2019, pp. 510–522.
[89] V. Padilha, F. de Oliveira, D. Proverbs, S. Füchter, Innovative applications of VR: flash-flood control and monitoring", IEEE International Symposium on Measurement and Control in Robotics,Houston, TX, USA, (2019) A2-4-1-A2-4-3.
[90] Y. Sermet, I. Demir, Flood action VR: a virtual reality framework for disaster awareness and emergency response training, International conference on modelling, simulation and visualization methods (2019) 65–68.
[91] C. Wang, J. Hou, D. Miller, I. Brown, Y. Jiang, Flood risk management in sponge cities: the role of integrated simulation and 3D visualization", Int. J. Disaster Risk Reduc. 39 (2019) 101139.
[92] Y. Wu, F. Peng, Y. Peng, X. Kong, H. Liang, Q. Li, Dynamic 3D simulation of flood risk based on the integration of spatio-temporal GIS and hydrodynamic models, ISPRS Int. J. Geo-Inf. 8 (11) (2019) 520.
[93] C. Skinner, Flash Flood: a Serious Geo Games activity combining science festivals, video games, and virtual reality with research data for communicating flood risk and geomorphology, Geoscience Communication 3 (1) (2020) 1–17.

[94] G. Zhi, Z. Liao, W. Tian, J. Wu, Urban flood risk assessment and analysis with a 3D visualization method coupling the PP-PSO algorithm and building data, J. Environ. Manag. 268 (2020) 110521.
[95] J. Mol, W. Botzen, J. Appendices, After the virtual flood: risk perceptions and flood preparedness after virtual reality risk communication, Judgment and Decision Making 17 (1) (2022) 189.
[96] B. Yang, J. Ma, G. Huang, D. Cao, Development and application of 3D visualization platform for flood evolution in Le'an river basin of Wuyuan, IOP Conf. Ser. Earth Environ. Sci. 638 (2021) 12053.
[97] P. Haynes, S. Hehl-Lange, E. Lange, Mobile augmented reality for flood visualisation, Environ. Model. Software 109 (2018) 380–389.
[98] D. Mirauda, U. Erra, R. Agatiello, M. Cerverizzo, Mobile augmented reality for flood events management, Water Stud. 47 (2018) 418–424.
[99] M. Bartos, B. Kerkez, Pipedream: an interactive digital twin model for natural and urban drainage systems, Environ. Model. Software 144 (2021) 105120.
[100] M. Truu, I. Annus, J. Roosimägi, N. Kändler, A. Vassiljev, K. Kaur, Integrated decision support system for pluvial flood-resilient spatial planning in urban areas, Water 13 (23) (2021) 3340.
[101] J. Zhu, L. Yin, J. Wang, H. Zhang, Y. Hu, Z. Liu, Dam-break flood routing simulation and scale effect analysis based on virtual geographic environment, IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sens. 8 (1) (2014) 105–113.
[102] S. Ackere, H. Glas, J. Beullens, G. Deruyter, A. De Wulf, P. De Maeyer, Development of a 3D dynamic flood WEB GIS visualisation tool, Flood Risk Management and Response 3 (2016) 560–569.
[103] P. Haynes, E. Lange, Mobile augmented reality for flood visualisation in urban riverside landscapes, Journal of Digital Landscape Architecture 1 (2016) 254–262.
[104] R. Santis, F. Macchione, P. Costabile, C. Costanzo, A comparative analysis of 3-D representations of urban flood map in virtual environments for hazard communication purposes, in: E3S Web of Conferences, vol. 40, 2018 06037.
[105] R. Rydvanskiy, N. Hedley, Mixed reality flood visualizations: reflections on development and usability of current systems, ISPRS Int. J. Geo-Inf. 10 (2) (2021) 82.
[106] W. Su, Y. Lin, C. Huang, C. Yang, Y. Tsai, 3D GIS platform for flood Wargame: a case study of new Taipei city, Taiwan, Water 13 (16) (2021) 2211.
[107] V. Bakhtiari, F. Piadeh, K. Behzadian, Application of Innovative Digital Technologies in Urban Flood Risk Management, EGU23 conference, Vienna, Austria, 2023, https://doi.org/10.5194/egusphere-egu23-4143.
[108] L. Uscher-Pines, S. Fischer, I. Tong, A. Mehrotra, R. Malsberger, K. Ray, Virtual first responders: the role of direct-to-Consumer Telemedicine in caring for people impacted by natural disasters, J. Gen. Intern. Med. 33 (8) (2018) 1242–1244.