A Contemporary Systematic Review of Cyberinfrastructure Systems and Applications for Flood and Drought Data Analytics and Communication

Serhan Yeşilköy[a,b*], Özlem Baydaroğlu[b], Nikhil Singh[b], Yusuf Sermet[b], Ibrahim Demir[b,c,d]

[a] USDA-ARS, Adaptive Cropping Systems Laboratory, Beltsville, Maryland, USA
[b] IIHR Hydroscience and Engineering, University of Iowa, Iowa City, Iowa, USA
[c] Civil and Environmental Engineering, University of Iowa, Iowa City, Iowa, USA
[d] Electrical and Computer Engineering, University of Iowa, Iowa City, Iowa, USA

[*] Corresponding Author: S. Yeşilköy (serhan-yesilkoy@uiowa.edu)

Abstract

Hydrometeorological disasters, including floods and droughts, have intensified in both frequency and severity in recent years. This trend underscores the critical role of timely monitoring, accurate forecasting, and effective warning systems in facilitating proactive responses. Today's information systems offer a vast and intricate mesh of data, encompassing satellite imagery, meteorological metrics, and predictive modeling. Easily accessible to the general public, these cyberinfrastructures simulate potential disaster scenarios, serving as invaluable aids to decision-making processes. This review collates key literature on water-related disaster information systems, underscoring the transformative impact of emerging information and Internet technologies. These advancements promise enhanced flood and drought warning timeliness and greater preparedness through improved management, analysis, visualization, and data sharing. Moreover, these systems aid in hydrometeorological predictions, foster the development of web-based educational platforms, and support decision-making frameworks, digital twins, and metaverse applications in disaster contexts. They further bolster scientific research and development, enrich climate change vulnerability frameworks, and strengthen associated cyberinfrastructures. This article delves into prospective developments in the realm of natural disasters, pinpointing primary challenges and gaps in current water-related disaster information systems, and highlighting the potential intersections with future artificial intelligence solutions.

Keywords: Flood, Drought, Natural Disasters, Information Systems, Web Platforms, Cyberinfrastructure

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1. Introduction

According to the International Disaster Database EM-DAT (2022), the number of hydrometeorological disasters (e.g., flood and drought) has been increasing globally since the 1990s. The number of flood events doubled in the 1990s (862 events) to the 2010s (1733 events). The number of drought events increased from 140 to 179 at the same time period. Total damage was reported as US$220 billion and US$1.1 trillion in floods and droughts, respectively. In recent years, many researchers across the world have indicated that flood and drought events have increased not only in number but also in severity and frequency (Spinoni et al., 2014). The Clausius-Clapeyron equation of thermodynamics states that for every 1°C rise in air temperature, the atmosphere can sustain 6–7% additional moisture (Allen and Ingram, 2002; Trenberth et al., 2003). Studies have shown that the water availability in the atmosphere and evapotranspiration rates have both risen, leading to a more intense water cycle (Tabari, 2020) that causes flood and drought events to be experienced more severely and more frequently. Recent studies and multi-model ensemble climate projections highlight the increase of frequency and severity of drought and flood events in the 21st century (Madakumbura et al., 2019; Di Sante et al., 2021; Hirabayashi et al., 2021; Haltas et al., 2021) at several global (Spinoni et al., 2020; Wang et al., 2021), regional (Cos et al., 2022; Satoh et al., 2022), and watershed scales (Yeşilköy and Şaylan, 2022).

Moreover, many climate change studies have indicated that the number of floods including flash/mega floods and droughts will become stronger with the seasonal cycle of the atmospheric water availability (Chagas et al., 2022). These extreme dry and wet events can co-occur consequently in a short period around the world. Two examples in this regard are as follows. Japan experienced a flood event after one of the most impactful heatwaves in 2018 (Wang et al., 2018), and California, US experienced an hazardous flood in 2018 after a long-lasting drought duration between the years 2012 and 2017 (Ward et al., 2021).

Drought is considered a multidimensional and insidious hydrometeorological and climatological hazard causing adverse impacts on agriculture, water supplies, recreation, wildlife, and society in terms of gradual occurrence and long-lasting impacts (Harishnaika et al., 2022; Saharwardi et al., 2022). Due to its physical and dynamical complexity, researchers have tried to understand drought dynamics with various machine learning (ML) and deep learning (DL) methods and indices. Precipitation, soil moisture, wind, and a water-vapour deficit are the prevailing factors of drought initiation and propagation (Schumacher et al., 2022). These atmospheric factors are incredibly challenging to forecast because of their high spatiotemporal variability (Tijdeman et al., 2022), chaotic nature, and extreme sensitivity to initial conditions (Baydaroğlu Yeşilköy et al., 2020). Given the large spatial variability of these meteorological variables, monitoring drought conditions is a challenging task. Indeed, this is why plenty of drought indices exist. Numerous studies have investigated the capacity of flood forecasting (precipitation, flow and water level) using deep learning (DL) (Sit et al., 2021a; Mosavi et al., 2018; Gautam et al., 2022), physical models (Jain et al., 2018), hybrid methods (Baydaroğlu et al., 2018), remote sensing (Kuenzer et al., 2013), and crowdsourced data collection (Sermet et al., 2020a) and instrumentation (Muste et al., 2017). In addition, large-scale benchmark datasets are created that may contribute to flood predictions (Demir et al., 2022; Sit et al., 2021b).

In this digital era, remote sensing, sensor networks, data-driven models and crowdsourcing efforts create tremendous amounts of data. The digital data grows exponentially and is expected to reach 175 zettabytes (Reinsel et al., 2018) by 2025 and the doubling rate will be maintained every two years (Ye and Li, 2017). The data is heterogeneous, and problems stemming from heterogeneity are very common in the domain of earth science (Demir et al., 2015). These data may be managed and analyzed as a consequence of developments and new approaches in information technology. Information systems are computer-based platforms that can access a wide range of data that has been acquired, stored, or managed to deliver targeted insights that assist in decision support (Wiederhold, 1992). Information systems provide a range of capabilities for decision making while enabling people to access, analyze, and explore data and information quickly and efficiently (Demir and Beck, 2009; Jones et al., 2018).

This study provides a comprehensive review of hydrometeorological disaster information systems, focusing on flood and drought domain. The rise in the frequency and severity of these disasters necessitates the development of advanced systems that can monitor, forecast, and issue warnings to help mitigate their impact. The paper examines the current state-of-the-art in flood and drought information systems, including their design, implementation, and capabilities. Additionally, it highlights the key challenges and difficulties faced by these systems and provides recommendations for future research. The study’s main contribution is to provide an overview of the current state-of-the-art in hydrometeorological disaster information systems, highlighting the advances made in this field and identifying areas where further research is needed.

The manuscript was structured as follows: Section 2 explains the literature search criteria and methodology reviewing the active web platforms. Related works, impacts of flood and drought events, other findings can be found in Section 3. Key issues and recommendations were described in Section 4. Some suggestions can be found in Section 5.

1.1. Background

Climate projections have previously indicated that there would be a rise in floods and droughts as a result of climate change. Figure 1 shows a rise in both flood and drought events, particularly between 1990 and 2000 using the EM-DAT disaster repository. While floods and droughts are both hydrometeorological disasters, their onset and effect periods differ. Moreover, long-term flood and drought indicators should be examined in order to provide a clear explanation for natural disasters caused by climate change. Even so, Figure 1 clearly shows the rise in floods and droughts.

Figure 1 also shows that, although the frequency of floods has grown, the number of persons impacted by floods has reduced (Fig. 1a). The reasons for this can be attributed to the development of forecasting models for hydrometeorological variables related to floods, the use of various types of data in these forecasting models and high-performance computing, the timely access to forecast results and potential scenario simulations, dissemination of flood warnings to relevant stakeholders and support for decision support systems via cyberinfrastructures. In Figure 1(b), it is seen that the number of people affected by drought increased in proportion to the increase in the number of drought events between 1990 and 2000. The people impacted by drought reduced between 2000 and 2010, despite a minor rise in the frequency of drought occurrences. Although it is a disaster that requires a longer forecasting period, progresses more insidiously, and takes time to generate results compared to floods, it can be thought that better planning reduces the number of people affected due to forecasting algorithms, information systems, and technological progress.

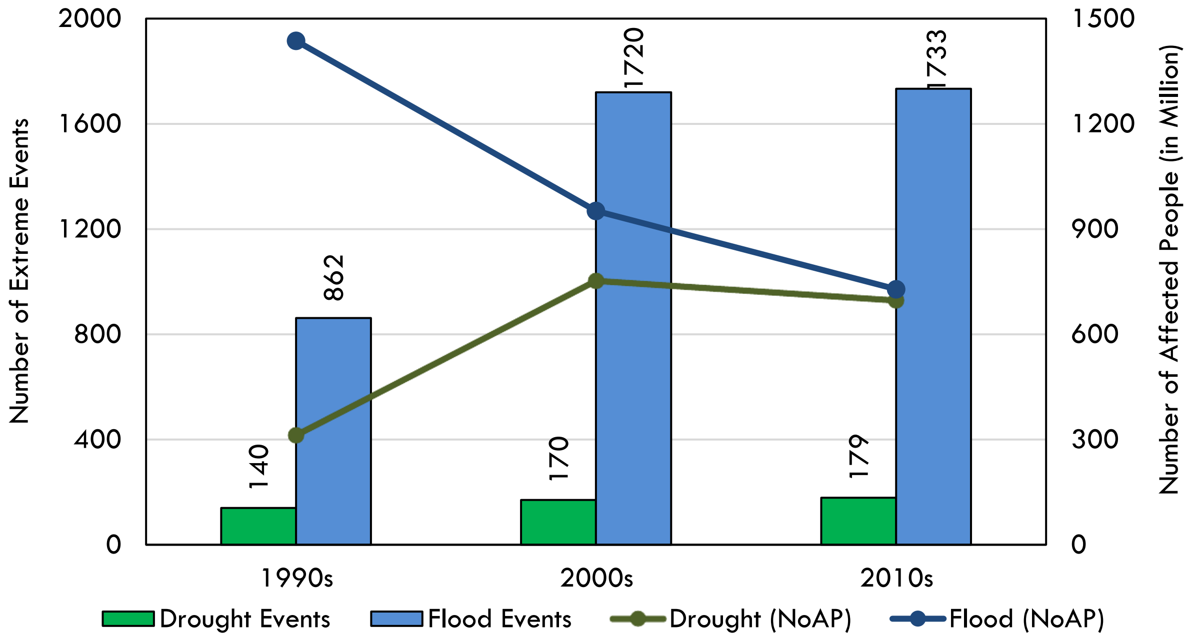

Figure 1. Bars and lines represent the number of events and affected people in (a) flood and (b) drought events, respectively (Source: EM-DAT).

The increasing impact of climate change on hydrometeorological disasters, such as floods and droughts, has created an urgent need for effective information systems to manage and mitigate their effects. These systems play a crucial role in monitoring and predicting events, enabling stakeholders to make informed decisions about mitigation and adaptation strategies. The historical context of flood and drought information systems dates back to early efforts to monitor and predict these disasters. Over time, technology and methodologies have evolved, leading to the development of more sophisticated and accurate information systems.

Remote sensing, ground-based measurements, and modeling techniques have played a significant role in monitoring and predicting flood and drought events. However, integrating these diverse data sources into information systems presents numerous challenges. Effective communication, visualization, and decision support tools are essential in flood and drought information systems, enabling stakeholders to make informed decisions about mitigation and adaptation strategies.

Recent advancements in technology, such as artificial intelligence (AI), machine learning, and big data analytics, have the potential to revolutionize flood and drought information systems by improving prediction accuracy and enhancing decision-making capabilities. Open-source software, community engagement, and collaborative efforts are instrumental in the development of flood and drought information systems, promoting transparency, accessibility, and innovation in this field.

Implementing flood and drought information systems at different spatial scales (e.g., global, regional, local) and in various socio-economic and environmental contexts presents both challenges and opportunities. It is increasingly important to consider social, economic, and environmental factors in the design and implementation of these systems. Interdisciplinary research and collaboration are vital in addressing the complex and interrelated issues surrounding flood and drought events.

Therefore, this review study aims to provide a comprehensive overview of the current state-of-the-art in flood and drought information systems, highlighting the advances made in this field and identifying areas where further research is needed. By examining the challenges and opportunities associated with the development and implementation of these systems, we hope to contribute to the ongoing efforts to improve their effectiveness in managing and mitigating the impacts of hydrometeorological disasters.

2. Methodology

2.1. Scope and Purpose

The primary aim of this systematic review is to provide a comprehensive assessment of the existing flood, drought, and water quality hazards information systems identified through our systematic literature search. To achieve this goal, we formulated the following research questions (RQ) that guided our analysis and discussion:

RQ1. What are the main features and capabilities of the current state-of-the-art in flood and drought information systems, and how do they address the needs of various stakeholders?

RQ2. How do these information systems incorporate and utilize different data sources, data processing techniques, modeling, forecasting, and communication approaches to support decision-making processes?

RQ3. What are the key challenges and difficulties faced by flood and drought information systems, and how can these be addressed in future research and development efforts?

RQ4. How have technological advancements and the growing availability of data impacted the design, implementation, and effectiveness of hydrometeorological disaster information systems?

By addressing these research questions, our review provides valuable insights into the current state-of-the-art in hydrometeorological disaster information systems, highlighting the advances made in this field, and identifying areas where further research and development are needed.

2.2. Literature Review Procedure

This review is conducted using a systematic literature search in hydrometeorology and hydroclimatology domains. Key information regarding the review process (e.g., databases, keywords, fields) is described in Figure 2. In the first stage, articles published from 2010 to 2022, August were gathered based on their compliance with the keyword search criteria, which comprise titles, abstracts, and keywords linked to subject areas. A total of 1,711 publications were found under these search conditions. All these papers were examined meticulously, and the papers which include the publicly available drought or flood information system, were included in this review. 88 publications and 111 information systems (without publications), which were mentioned in the references of these articles, remained after the filtering and were used in this review. Beside scientific databases, a manual exploration of Google search results was performed, employing the specified keywords to detect any relevant web platforms lacking associated publications in the scholarly domain. The references of the studies were also scanned in order not to overlook them.

To ensure the relevance and quality of the publications included in this review, we established specific inclusion and exclusion criteria. The inclusion criteria consisted of articles that focus on the development, implementation, or evaluation of web-based flood or drought information systems, as well as articles that describe publicly available drought or flood information systems. On the other hand, the exclusion criteria were designed to filter out articles that do not focus on web-based information systems for flood or drought management, primarily emphasize water quality information systems unrelated to hydrometeorological disasters, or do not provide sufficient details on the information systems being discussed. By applying these criteria, we ensured that our review focused on the most relevant and informative publications in the field of hydrometeorological disaster information systems.

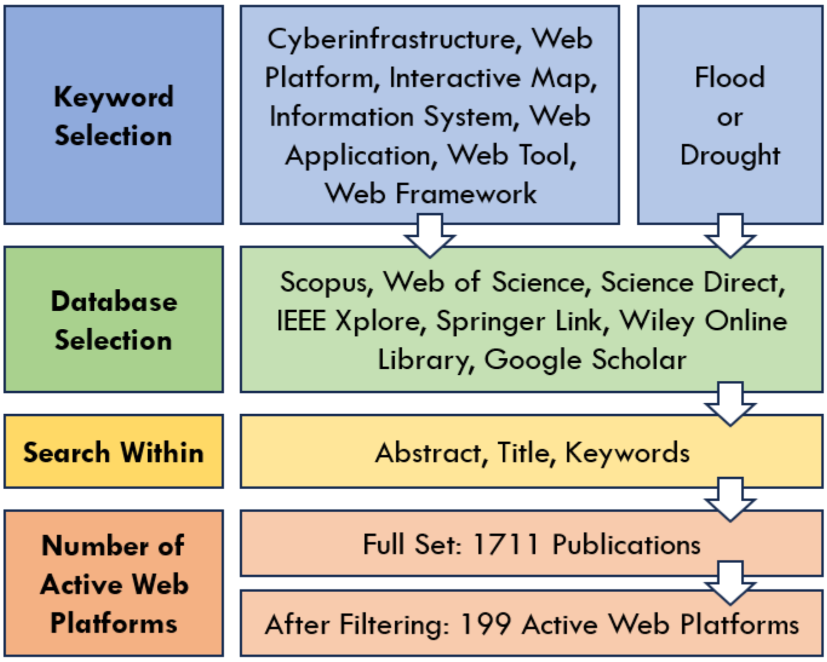

Figure 2. Search methodology process and corresponding steps

2.3. Literature Review Parameters

To systematically analyze the selected information systems, we extracted various features and aspects that are instrumental in addressing our research questions. These review parameters encompass a wide range of attributes related to the design, implementation, and capabilities of the hydrometeorological disaster information systems. By examining these parameters, we provide a qualitative and quantitative analysis of the current state-of-the-art and establish trendlines for future work in this field. These parameters capture the essential characteristics of the hydrometeorological disaster information systems and enable a structured comparison and analysis of their features, capabilities, and performance. By analyzing these review parameters, we can better understand the strengths and weaknesses of existing disaster information systems and provide recommendations for future research and development in this area. Table 1 describes the review parameters used in reviewing the elicited information systems along with their descriptions.

Table 1: Summary of literature review parameters related to the design, implementation, and capabilities of the hydrometeorological disaster information systems

Parameter	**Description**
Platform Name	The name of the information system or web platform
Focus Area	The specific hydrometeorological disaster(s) that the system focuses on (e.g., flood, drought, water quality)
Audience	The target user group(s) for the system (e.g., public, professionals, students)
Purpose	The main goal or objective of the system (e.g., monitoring, decision support, education)
Use Cases	Specific applications or scenarios where the system can be employed
Outlook Modeling	The use of forecasting models or simulations in the system
Location Coverage	The geographical scope of the system (e.g., global, regional, country, watershed)
Location Category	The spatial scale of the system (e.g., city, county, state, basin)
Release Year	The year the system was launched or became publicly available
Assessment	Whether an evaluation of the system's performance or effectiveness is conducted
Open-Source	Whether the system's source code is publicly available and open for contribution
Map Provider	The provider of the base map used in the system (e.g., Google, Bing, OpenStreetMap)
Database	The database technology used in the system (e.g., PostgreSQL)
API	The application programming interface used in the system (e.g., Swagger)
Backend	The backend technology or framework used in the system (e.g., NodeJS)
Frontend	The frontend technology or framework used in the system (e.g., React)
Mobile Support	The availability of mobile support for the system
VR/AR Support	The use of virtual, augmented, or mixed reality in the system
Digital Twin	The implementation of a digital twin representation of the physical environment
3D Visualization	The use of 3D visualization techniques for data presentation
WebGL	The use of WebGL technology for rendering graphics

WebAssembly	The use of WebAssembly for executing code in web browsers
IndexedDB	The use of IndexedDB for client-side storage of data
Service Workers	The use of service workers for background tasks and offline support
Web Workers	The use of web workers for running background tasks in parallel
Notifications API	The use of the Notifications API for sending notifications to users
Push API	The use of the Push API for delivering messages to users

3. Results

We present a comprehensive assessment of the existing flood, drought, and water quality hazards information systems identified through our systematic literature review. The assessment is divided into three main subsections: a) *Summary of Findings*, which provides a concise overview of the key trends derived from our analysis, supported by charts and numerical data; b) *Assessment by Focus Area*, where we evaluate the information systems based on their specific focus areas while considering their application domains such as monitoring, early warning, risk assessment, and decision support; and c) *Assessment by Technological Capabilities*, where we analyze the systems in terms of their data sources, processing techniques, modeling and forecasting communication approaches, and web-based platform features. To provide a structured framework for our assessment, we refer to Figure 3, which illustrates the conceptual framework of a web-based information system (IS) for floods, droughts, and water quality hazards. This framework serves as a guide for our analysis, allowing us to identify trends, strengths, and weaknesses within the current state-of-the-art in information systems on water-related disasters.

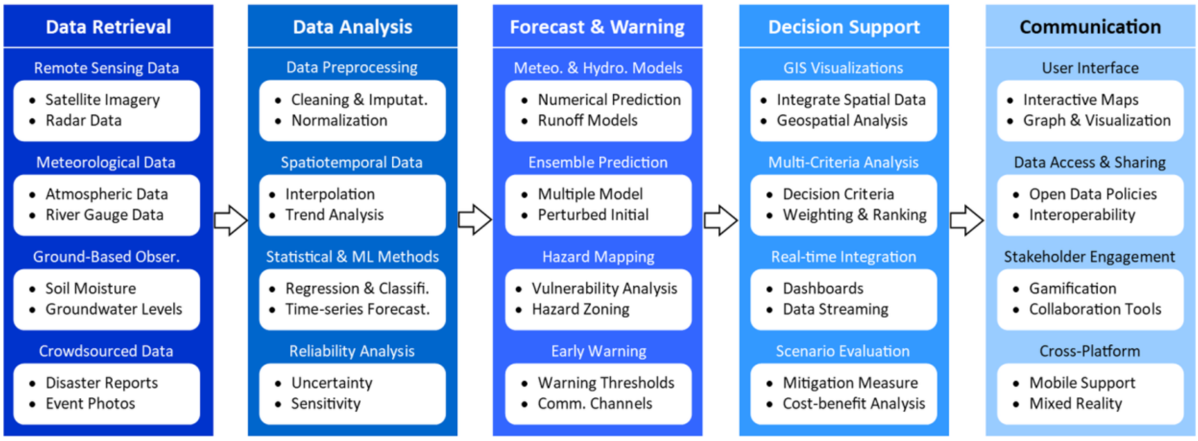

Figure 3. Conceptual framework of a web-based IS for hydrological disasters.

3.1. Overview of Findings

Our review highlights an increasing trend in the number of articles on water-related hazards information systems in recent years, as shown in Figure 4, with a total of 88 publications. The publications are predominantly focused on flood information systems, with 72 publications covering floods and 16 publications covering droughts, as illustrated in Figure 4. It should be noted that these charts reflect the trends in relevant publications as part of this review (n=88), and not the total identified information systems (n=199) due to lack of data.

The incorporation of outlook modeling, such as forecast models and serious games, is observed in 46% of the investigated flood and drought information systems. In terms of spatial scale, most cyberinfrastructures are developed at the national level, as shown in Figure 5. A distinction can be made between operational and informational cyberinfrastructures. While operational web platforms focus on process-oriented data access at smaller scales, informational cyberinfrastructures provide subject-oriented information access at larger scales. Figure 6a presents the distribution of operational and informational web platforms between the years 2010 and 2022.

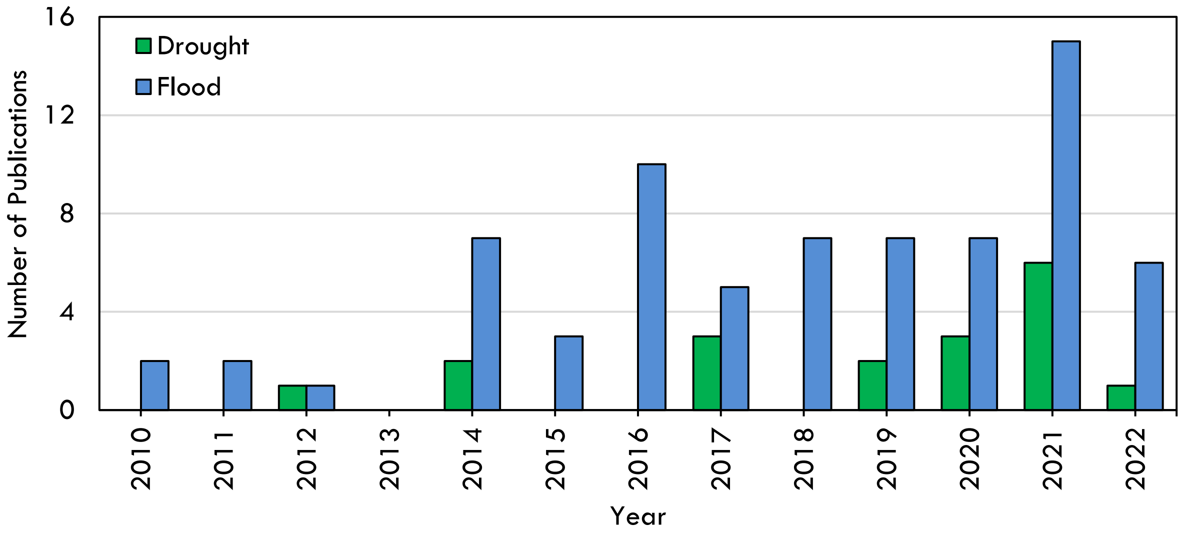

Figure 4. Number of publications by years in flood and drought domain.

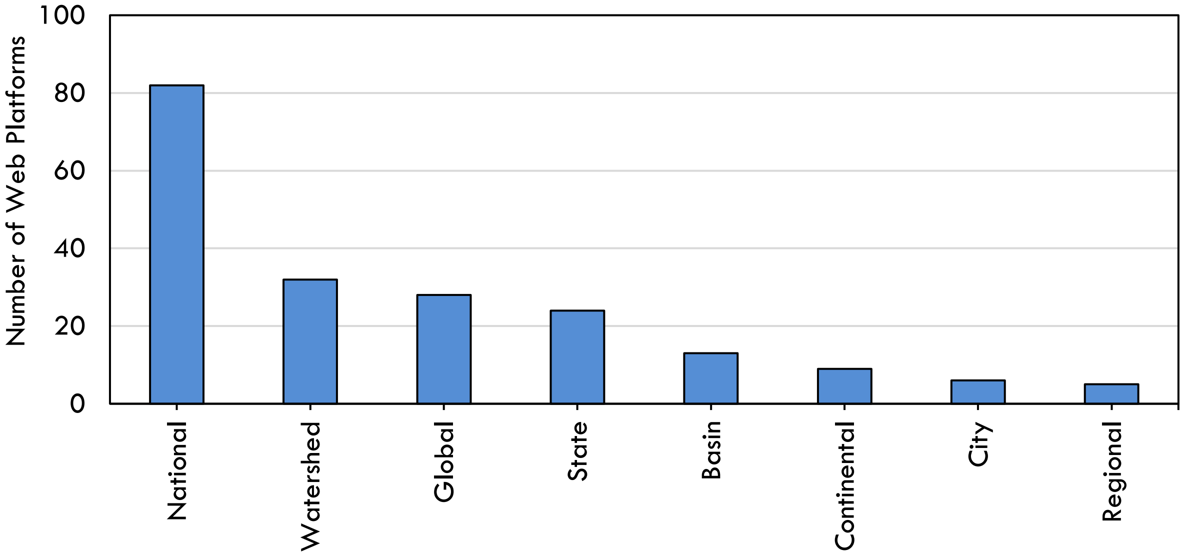

Figure 5. Location categories of hydrometeorological disaster web platforms.

In this review, we excluded water quality information systems that are not specifically related to hydrometeorological disasters. However, some of the identified information systems encompass both flood, drought and/or water quality aspects. As seen in Figure 6(b), the number of flood-related information systems is more than three times that of drought-related cyberinfrastructures. Additionally, there are more information systems covering floods and water quality than those covering droughts and water quality. Only four cyberinfrastructures were found to cover flood, drought, and water quality disasters simultaneously.

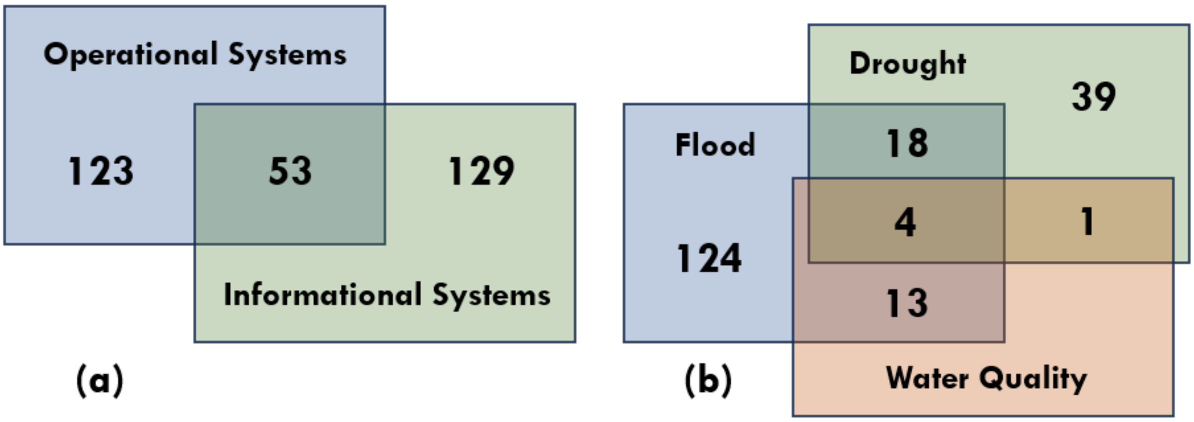

Figure 6. (a) The number of operational and informational water-related hazards web platforms between the years 2010 and 2022; (b) Number of information systems by focusing on natural disaster types.

3.2. Assessment by Domain Focus

Some web platforms are combined with flood, water quality (Hersh and Maidment, 2010; Li et al., 2018; Hafit et al., 2020; Oppus et al., 2021; Demir et al., 2009), drought (Balbo et al., 2013; Cristofori et al., 2015; Aadhar and Mishra, 2017; Sattaru et al., 2021), drought and water quality (Kakalia et al., 2021) to generate hybrid information systems. In this review, flood and drought cyberinfrastructures are investigated seperately.

3.2.1. Flood Information Systems

Flood risk management is a complex process that involves many public and constitutional stakeholders. It needs to use cutting-edge analytical and communication technologies to process data and information in real time. Flood Information Systems play a key role in giving early warnings and reducing damage from flooding (Weber et al., 2018) by using data-driven risk analysis for disaster-prone communities and using cutting-edge statistical methods and data generation to improve analysis of rare and catastrophic natural disasters. Recent developments in information and internet technologies provide a great opportunity to enhance all the aforementioned data processes and sharing of flood and rainfall-related data and information and to improve the timeliness of flood warnings (Demir and Krajewski, 2013).

The domain of flood cyberinfrastructures has seen transformative advancements in recent years (Curtis and Fowler, 2012; Andreasen et al., 2016; Escudier et al., 2016; Jones et al., 2017; Borsch et al., 2018; De Filippis et al., 2022). This growth is underscored by the development of multi-hazard and multi-criteria platforms (Ries et al., 2010; Heil et al., 2014; Kochilakis et al., 2016; Ong et al., 2017; Abily et al., 2020; Lin et al., 2020; Mamassis et al., 2021). Concurrently, digital watershed designs have emerged (Qiu et al., 2022), complemented by reservoir inundation mapping tools (Aekakkararungroj et al., 2020) and specialized Python utilities (Christensen et al., 2017). The embrace of crowd intelligence, notably via natural language processing of tweets (Donratanapat et al., 2020), has been enhanced through high-performance computing (Svatoň et al., 2018; Bottazzi et al., 2021) and satellite data analytics (Craciunescu et al., 2016). These integrated approaches have fortified estimations of natural hazards vulnerability (Rod et al., 2014; Erikson et al., 2018) and strategies for urban resilience (Villani et al., 2019).

Modern modeling frameworks are being incorporated widely (Georgas et al., 2016; Palla and Gnecco, 2021), alongside initiatives that champion public participation (Henriksen et al., 2018; Horsburgh et al., 2019; Tripathy and Malladi, 2022) and provide nuanced hydrogeomorphic descriptions (Da Costa et al., 2019). Novel technologies, such as surge-wave web-based systems (Khalid and Ferreira, 2020), real-time 3D flood simulations (Spaulding et al., 2017; Khoury et al., 2017; Bauer et al., 2019; Mourato et al., 2021), and tools that offer immersive 3D earth structure visualizations (Kilsedar et al., 2019), are being developed. There's also a growing interest in interactive web narratives that shed light on current and prospective flood threats (Oubennaceur et al., 2021). Additionally, historical isotopic data related to waters is being collated (Ahmed et al., 2022), marked by advancements in API technology (McMahan et al., 2021) and open-source libraries with APIs (Lagmay et al., 2017).

Some web-based decision support systems can be considered educational and/or informational tools, including risk scenarios or allowing their users to change the drivers and provide risk evaluation for diverse purposes (Jones et al., 2014; Knight et al., 2015). For instance, MiDAS (Mitigation and Damage Assessment System) evaluates the community's flood risk at the property level in Iowa (Alabbad et al., 2022), and the Prairie Pothole Management Support Tool (PPMST) estimates the flood risk of individual farmed prairie potholes in Iowa (Nahkala et al., 2022). Some of these web tools creates flood plain maps for the Mississippi River Basin (Rajib et al., 2021), flood hazard and risk maps for Armenia (Dobrinkova and Stefanov, 2020), Bangladesh using LiDAR technology (Tupas et al., 2016), for families, buildings, population, industries, and cultural heritages in Italy (Iadanza et al., 2021), and evaluates the vulnerability of an urban system to the effects of disasters for City of Toronto and London in Canada (Irwin et al., 2016).

Serious gaming frameworks are becoming more common with studies for San Antonio, US (Carson et al., 2018; Sermet et al., 2020b) and under different climate change scenarios by combining a sensitivity framework with a grid-based hydrological model across Great Britain (Kay et al., 2021), and creates a worldwide natural disaster risk data platform including flood (Giuliani and Peduzzi, 2011) using citizen science based on tweets (De Bruijn et al., 2019). They also have the capability to share and download datasets and upload new ones. Some operational warning systems, like ITHACA (Information Technology for Humanitarian Assistance, Cooperation, and Action), use global datasets based on near real-time satellite and radar imageries (Agosto et al., 2011). They focus on a 36-hour flood forecast at street-level (Loftis et al., 2019), a 60-hour flood risk forecast including soil saturation data (Alcantara et al., 2018), and a weekly flood forecast based on a hydrological model (Artinyan et al., 2016). Some of these systems are cloud-based and use GPU to speed up model run time compared to CPU for predicting effects on transportation infrastructure systems (Morsy et al., 2018), or presents a tool for modeling flood risk instantly (Ngo et al., 2021).

Some of these web platforms can be considered not only operational but also as a decision support system. They provide both real-time (or near-real-time) precipitation from satellites and/or radars, gauge measurements, and flood-risk maps with several return periods. IFIS (Krajewski et al., 2017) and NOAH (Rodrigez et al., 2017) can be examples of these web platforms. Many institutions and organizations have migrated flood-related data and information to web-based settings due to recent web technology advancements. Smartphones and other portable devices allow internet-based usage of these systems anywhere and anytime (Demir and Krajewski, 2013).

3.2.2. Drought Information System

In recent years, drought information systems have started to place a greater emphasis on disaster mitigation and resilience improvement (Thomas et al., 2020; Shukla et al., 2021). Many countries, ministries, disaster management and research centers have established information systems or web platforms to inform stakeholders (public, farmers, energy and recreation centers etc.) by using different methods and data (i.e., gauge, satellite) sources to monitor drought and its adverse impacts.

To monitor meteorological, agricultural (Sun et al., 2017), and hydrological drought events and their severity, these cyberinfrastructures provide crop vegetation conditions, streamflow, soil moisture deficit, rainfall patterns, real-time data, and warnings with various drought indicators at not only global (Sohn et al., 2012; Deng et al., 2013; Nijssen et al., 2014; Hao et al., 2014), regional, and watershed scale (Shukla et al., 2021) but also semi-arid climatic regions (Vicente-Serrano et al., 2022) around the world. These web platforms also enable weekly, monthly, and seasonal drought-related potential impact reports for agricultural sectors (Rembold et al., 2017) based on different agroclimatic indicators, public health, tourism, livestock (Stone et al., 2019), and other related communities (McCullum et al., 2021). They also use various drought indices, which have different representativeness capacities for different types (meteorological, hydrological, agricultural) of drought including snow (Hatchett et al., 2022).

These web systems have capacities for real-time or timely warning (Rembold et al., 2017), short-term (1-2 weeks), and seasonal (1-3 months) forecasts (Saha et al., 2021), mitigation, susceptibility (Balbo et al., 2013), and drought impacts on crop yields, groundwater use (Thomas et al., 2020), based on gauged measurements, remotely-sensed, or a combination of these data types. These platforms allow their users to compare drought maps (Nijssen et al., 2014) with different time scales and indices (i.e., EDDI, PDSI, SPI, SPEI), create time series (Gorsevski et al., 2021) and maps over the selected region, select different data sources (Sun et al., 2020; Kakalia et al., 2021), instantly visualize model (i.e., VIC, Noah) output (Aadhar and Mishra, 2017), gauge measurements, gridded reanalysis (e.g., ERA5), and remote sensing data (GRACE, SMAP, MODIS, etc.) (Ndungu et al., 2019; McStraw et al., 2021).

They also generate weekly or monthly bulletins for the specific field crops (i.e., winter wheat, rice, maize) (Sattaru et al., 2021), vegetables, and trees, and download the drought-impacted areas (Trnka et al., 2020) for the professionals with different data formats. Some platforms (Water Data for Texas, National Integrated Drought Information System, and Midwestern Regional Climate Center) investigate the relationships between atmospheric teleconnections patterns (such as the El Niño Southern Oscillation, ENSO), atmospheric rivers, and current drought conditions. Data sets from the Global Integrated Drought Monitoring and Prediction System (GIDMaPS) (Hao et al., 2014) gives drought information based on several drought indicators.

A cloud-based system for monitoring and predicting worldwide agricultural droughts was developed by Sun et al. (2019), and it offers scalable vegetation-based drought indicators generated from data on satellite- and model-based vegetation conditions. Following the development of information systems for flooding, drought information systems with a longer occurrence period were created. Some of the drought cyberinfrastructures contain decision support capabilities, while others are just for warning reasons.

3.3. Assessment by Technological Capabilities

This section provides findings in the technological landscape of hydrological information systems. It is important to note that this might not fully represent the state of systems developed and used in the sector, as the technical parameters are mainly available when the developers willingly share these details in publications or on their websites. Nonetheless, they offer valuable insights into the common technological choices made by academics and scientists in this field.

Based on our analysis, PostgreSQL was found to be the most commonly used database, with a significant number of systems utilizing it. This may reflect the preference for PostgreSQL in academia due to its open-source nature, robustness, and compatibility with various programming languages. However, it should be noted that our results may not be indicative of the broader industry trends.

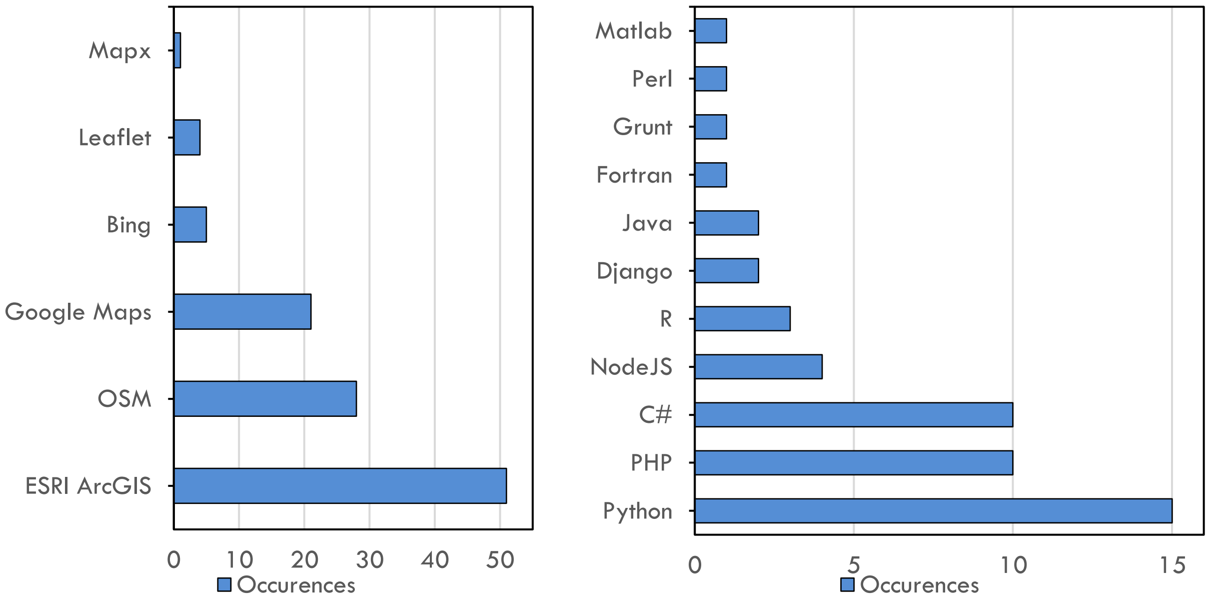

Figure 7. Distribution of IS (a) map providers (n=110) and (b) backend technologies (n=50)

In terms of backend technologies, we observed a variety of programming languages and frameworks being employed in the development of these information systems (Figure 7b). The most frequently used backend languages are Python, followed by PHP and C# (ASP.NET). This suggests that these languages are popular choices for building hydrological information systems in academic settings, likely due to their flexibility, ease of use, and extensive libraries.

Regarding map providers, ESRI ArcGIS was found to be the most popular choice among the systems reviewed (Figure 7a). This could be attributed to the comprehensive features and tools provided by the ArcGIS platform, which cater to a wide range of spatial analysis and geoprocessing tasks. OpenStreetMap (OSM) and Google Maps were also frequently used. The popularity of these map providers can be attributed to their accessibility, ease of integration, and extensive map coverage.

Continuing the assessment of technological capabilities, we examined the usage of modern and experimental technologies in hydrological information systems. Figure 8 presents the number of systems employing features such as WebAssembly, WebGL, 3D visualization, AR/VR/XR, Web Workers, Notification API, Service Workers, Push API, and IndexedDB. These advanced technologies offer potential opportunities for enhancing the capabilities and user experience of hydrological information systems.

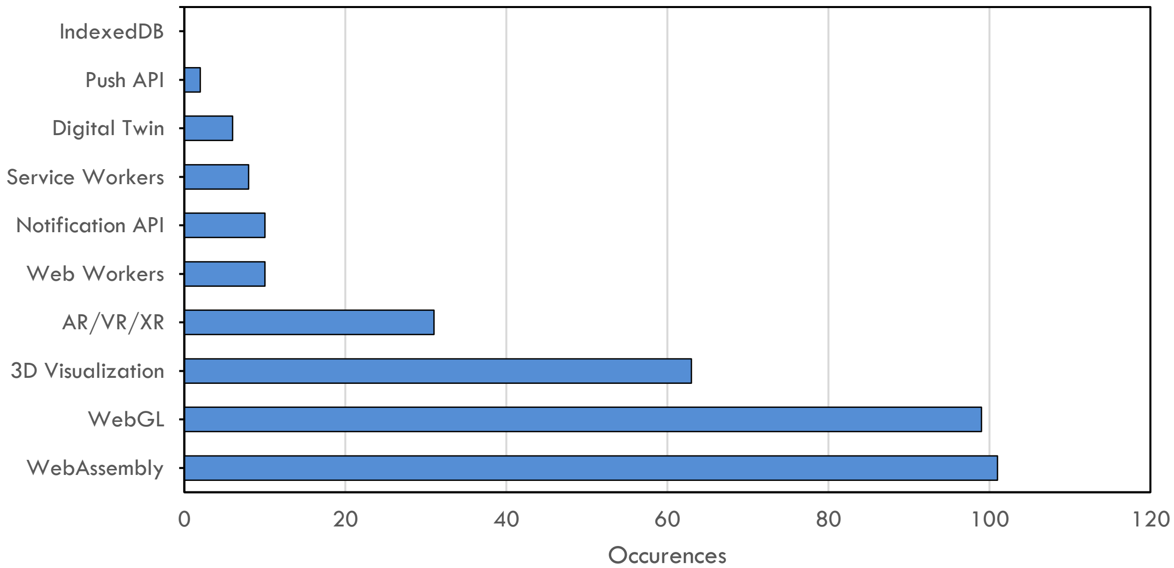

Figure 8. The number of information systems employing modern technological features.

Our analysis reveals that WebAssembly and WebGL are the most prevalent modern technologies used in the reviewed systems. These technologies allow for high-performance computation and graphics rendering in web browsers, which can significantly improve the visualization and analysis capabilities of hydrological information systems. However, it should be noted that some occurrences might be due to integrations or modules within a website, such as Google Earth, and may not directly imply that these technologies are truly leveraged in hydrological IS design.

3D visualization is found to be employed in a substantial number of systems, providing more realistic and immersive representations of hydrological data. This technology can enhance users' understanding of complex spatial relationships and facilitate more effective decision-making. Augmented and virtual reality technologies are utilized in fewer systems, offering immersive and interactive experiences that can potentially improve user engagement and learning outcomes.

In addition to these visualization technologies, we discovered that even fewer systems incorporate Digital Twin technology. DT are virtual representations of their physical counterparts, simulating real-world processes and conditions in a digital environment. By integrating Digital Twins into hydrological information systems, users can obtain a deeper understanding of the complex interactions between various hydrological parameters and their impacts on the environment. This advanced technology can also support scenario analysis, enabling stakeholders to evaluate different management strategies and mitigation measures before implementing them in the real world. The relatively low number of systems using DT technology highlights an opportunity for further exploration and adoption in the development of future hydrological information systems. By incorporating DTs, alongside 3D visualization and AR/VR technologies, information systems can provide more accurate, immersive, and interactive experiences for users, ultimately contributing to more effective decision-making and management of hydrometeorological disasters.

Web Workers, Notification API, Service Workers, and Push API are less commonly used in the reviewed systems. These technologies provide opportunities for background processing, real-time notifications, and offline support, which can significantly enhance the user experience and overall functionality of hydrological information systems. It is worth mentioning that the adoption of these technologies is still relatively low, representing untapped opportunities for hydrological stakeholders to further explore their potential benefits and applications.

Interestingly, none of the reviewed systems were found to utilize IndexedDB, a client-side storage technology that can be advantageous for managing large datasets, providing offline capabilities, and improving the performance of web applications. This finding suggests that there is room for further exploration and adoption of IndexedDB in the development of future hydrological information systems.

4. Discussions

In the discussions section, we address the limitations and challenges encountered during our review of hydrometeorological information systems and subsequently propose recommendations and future directions to enhance the development, implementation, and effectiveness of these systems in managing and mitigating floods and droughts.

4.1. Limitations and Challenges

In this review, we investigated active and publicly available systems and publications related to hydrometeorological information systems. However, most cyber systems did not have publications, which prompted us to perform a Google search using the predefined keywords, in addition to searching the scientific databases. Websites of major government agencies, especially the USGS and NOAA, were also searched for web-based information systems. This approach presented several challenges, the most crucial being the existence of information systems that cannot be accessed via the literature review. As the literature review was executed in the English language, it is probable that information systems featuring web pages in various languages (such as Chinese or Japanese) may exist but lacking scientific articles in English explaining these systems. Some information systems are actively used despite the absence of publications, while there are online platforms that were formerly operational but are now dormant, further complicating the review process.

Another limitation is that this review focuses on examining web platforms associated with hydrometeorological information systems. Although multiple academic publications may be associated with a single web platform, our review selected only one paper to represent each web platform (the most recent one for up-to-date information). This approach has a few limitations, such as the potential exclusion of valuable insights from other related publications. Furthermore, our results primarily provide details on systems with associated publications, which tend to emerge from academic environments. Consequently, the findings may predominantly reflect the status quo for information systems developed by academics and scientists, rather than those developed by the industry. This limitation may skew our understanding of the broader technological landscape in the field of hydrometeorological information systems.

An additional challenge is the lack of proper documentation and the inherent difficulty in methodically identifying the use of specific technologies within web platforms. Some reviewed platforms' technical details may not be fully accurate, which means that there may be a margin of error in the reported numbers. Moreover, it is not feasible for information systems that do not adhere to the FAIR (findability, accessibility, interoperability, and reuse) data principles to become widespread, evolve, or be integrated into decision support systems. This limitation highlights the importance of adopting FAIR data principles in the development of future hydrometeorological information systems.

Finally, notwithstanding the recent increase in interdisciplinary research, collaborations between environmental and computer sciences remain relatively restricted. This limitation is further exacerbated by the fact that environmental domain publications often leave out reporting technical details, which is a significant hindrance to reproducibility. Many papers reviewed under this study offered no information on implementation details. This lack of transparency and makes it difficult for other researchers to build upon existing work and develop more advanced hydrometeorological information systems.

4.2. Recommendations and Future Directions

In this section, we provide recommendations and future directions for enhancing the development, implementation, and effectiveness of hydrometeorological disaster information systems, addressing the limitations and challenges identified in our review.

Interdisciplinary collaboration: Promoting interdisciplinary collaboration between environmental and computer sciences is essential for advancing hydrometeorological information systems. Environmental science professionals should concentrate on informatics studies and expand collaborations between meteorologists, hydrologists, agriculturists, computer scientists, and web developers. By fostering interdisciplinary research, diverse perspectives and expertise can be leveraged to develop innovative solutions, improve system functionality, and ensure the systems are tailored to address the unique challenges associated with floods and droughts.

FAIR data principles: Ensuring that cyberinfrastructures adhere to FAIR data principles (findability, accessibility, interoperability, and reuse) is crucial for their integration with decision-making mechanisms and overall effectiveness. Adhering to these principles can increase the availability and utility of data, facilitating collaboration and knowledge sharing among researchers, practitioners, and stakeholders. This, in turn, can contribute to the development of more accurate, reliable, and effective flood and drought information systems.

Regional information systems: Developing regional information systems by merging local systems can enhance their utility and relevance by providing more comprehensive and contextualized information. Providing language alternatives for data and information exchange is also essential in accommodating diverse user groups, ensuring that the systems are accessible and usable across different regions and communities. The integration of local and regional information systems can facilitate a more coordinated and effective response to hydrometeorological disasters.

Integration with other disaster information systems: Integrating flood and drought information systems with other disaster information systems can offer a more comprehensive view of hazards and their interdependencies. This can enhance the understanding of the potential cascading impacts of multiple hazards and enable decision-makers to develop more effective and integrated disaster risk reduction strategies.

Agricultural Sustainability: Developing drought information systems is vital for improved monitoring, especially in the context of agricultural sustainability. This is particularly important considering the invasive and chaotic nature of droughts. Improved drought monitoring can enable informed decision-making related to water resource management, crop planning, and other aspects of agricultural production, ultimately contributing to greater resilience and sustainability in the face of increasing drought risks.

Water quality web platforms: Incorporating water quality web platforms into flood and drought information systems can provide a more holistic understanding of the relationships between different aspects of water management. This can help decision-makers identify potential trade-offs and synergies between flood and drought management strategies and water quality objectives, ensuring that water resources are managed sustainably and equitably.

Artificial intelligence: Utilizing artificial intelligence for data processing and prediction in flood and drought information systems can significantly enhance their capabilities and contribute to more effective disaster management. AI techniques, such as machine learning and deep learning algorithms, can enable the analysis of large and complex datasets, leading to more accurate and timely predictions of flood and drought events in a way that it is informed on the intricacies of the geographical region at hand.

Ontologies and knowledge graphs: Establishing ontologies and knowledge graphs for flood and drought cyberinfrastructures can improve their functionality and adaptability by providing a structured and standardized representation of the domain knowledge. Offering workshops and free practical training can facilitate the development and use of these ontologies and knowledge graphs, enabling researchers and practitioners to better understand and navigate the complex relationships between different variables and factors associated with floods and droughts.

Gamification for decision support systems and public awareness: Employing gamification in web-based tools can support decision-making processes and enhance public awareness by making complex information more engaging and accessible. Interactive interfaces can help users investigate difficulties and analyze the cost-benefit connections of hazard mitigation measures, fostering a greater understanding of the risks and potential solutions associated with floods and droughts. In addition, gamification can motivate users to learn more about hydrometeorological disasters and their impacts, ultimately contributing to more informed and resilient communities.

Digital Twins: Embracing the concept of digital twins in hydrometeorological information systems can offer significant advantages in terms of system performance, accuracy, and decision-making capabilities. DTs involve creating virtual representations of physical environments, enabling real-time monitoring and simulation of flood and drought events. By integrating DTs into information systems, decision-makers can gain a better understanding of the potential impacts of different scenarios and mitigation strategies.

Employing State-of-the-Art Web APIs: Utilizing state-of-the-art web APIs, such as WebGL, WebAssembly, IndexedDB, Service Workers, Web Workers, and WebGPU, can significantly enhance the performance, functionality, and user experience of hydrometeorological information systems. These advanced web technologies enable faster and more efficient data processing, improved graphics rendering, and better support for offline and parallel computing capabilities. By incorporating these cutting-edge web APIs into information systems, developers can ensure that their platforms remain up-to-date and provide users with the most effective and engaging tools for managing and mitigating hydrometeorological disasters while decreasing the cost of operation and long-term maintenance.

Blockchain and Decentralized Applications: Integrating blockchain technology and decentralized applications into hydrometeorological information systems can offer several benefits, including enhanced data security, transparency, and reliability (Satilmisoglu et al., 2022). Blockchain technology allows for the secure storage and sharing of data across a distributed network, ensuring that information is tamper-proof and easily verifiable. Decentralized applications built on blockchain platforms can facilitate increased collaboration and trust among stakeholders involved in flood and drought management, enabling more efficient and robust decision-making processes.

Technical documentation: Encouraging researchers to provide comprehensive technical documentation in their publications can enhance reproducibility and facilitate the sharing of best practices and methodologies. This can lead to a more collaborative and innovative research environment, enabling researchers to build on each other's work and develop more advanced and effective hydrometeorological information systems. By prioritizing technical documentation, the research community can ensure that knowledge is disseminated effectively and that progress in this field is accelerated.

Ultimately, these efforts can contribute to more effective management and mitigation of hydrometeorological disasters through the development of innovative and efficient information systems.

5. Conclusions

Water-related disasters, such as floods and droughts, have already started to rise, as predicted by climate projections. To reduce the loss of life and property caused by these natural disasters, it is becoming more vital to accurately predict these events, identify all probable scenarios, and communicate them with the public. Web-based information systems fulfill one or more of these hazard mitigation tasks, playing a crucial role in disaster management. This research presents a systematic review of cyberinfrastructures for hydrometeorological disasters, assessing their current state and identifying areas for improvement and future development.

Our findings reveal a rising trend in the number of flood and drought information systems in recent years, paralleling the increase in flood and drought occurrences. Floods are devastating, and our findings indicate that the creation of flood information systems will greatly aid in reducing the number of casualties and damaged properties. In contrast, droughts are challenging to identify due to their chaotic and insidious nature, resulting in more restricted effects of information systems in this domain.

The number of affected people from floods has been decreasing due to the enhanced streamflow prediction capacity, an increasing number of information systems, flood prevention structures (e.g., culverts, grade control structures, flood walls), and communication platforms like Twitter and Facebook. While approximately one-third of the cyberinfrastructures are both operational and informational, the informational ones are more numerous, highlighting the significance of their proliferation in providing timely and comprehensive information to users.

By promoting interdisciplinary collaboration, adopting FAIR data principles, and embracing advanced web and information technologies, we can strive to enhance the effectiveness of hydrometeorological information systems in managing and mitigating disasters, ultimately contributing to more resilient communities and sustainable water resource management.

6. Acknowledgements

The authors thank Jacob Nemec for providing valuable assistance towards the development of the presented framework. ChatGPT was utilized in the preparation of this article; any generated text is reviewed and revised for accuracy.

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