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Abstract

Urban hydrological infrastructure is vital for sustainable water management in cities, yet it faces significant challenges from climate change, rapid urbanization, and aging infrastructure. These challenges exacerbate water scarcity, increase flood risks, and strain existing infrastructure, underscoring the urgent need for innovative and adaptive solutions. Artificial Intelligence (AI) has emerged as a transformative tool, offering advanced capabilities in predictive maintenance, flood risk modeling, water quality monitoring, and urban planning. This study aims to explore AI's growing role in managing urban hydrological infrastructure. A qualitative approach was employed, utilizing a systematic review and bibliometric analysis to synthesize knowledge and identify trends in the field. Scopus was selected as the primary database due to its extensive coverage of multidisciplinary research. Keywords such as "urban hydrology," "artificial intelligence," "machine learning," "water management," "extreme events," and "flood prediction" were used, yielding a dataset of 2,098 relevant documents. The analysis identified five primary clusters of AI applications within urban hydrological infrastructure. These include AI in flood prediction and early warning systems, AI in urban water demand forecasting, AI in real-time water quality monitoring, AI in optimization of stormwater management systems, and AI in urban flood risk assessment and mapping. The originality of this research lies in its explorative analysis of AI's role in enhancing the efficiency, resilience, and sustainability of urban water systems. Furthermore, it offers practical insights for policymakers, engineers, and urban planners, paving the way for integrating cutting-edge technologies into urban water management. This study also contributes to the growing discourse on sustainable urban development, demonstrating how AI can revolutionize hydrological infrastructure to meet the demands of an increasingly complex and dynamic world.

Keywords: Artificial Intelligence (AI), Climate Change, Resilient Infrastructure, Stormwater Management, Sustainable Water Systems, Urban Flood Risk Assessment, Urban Hydrological Infrastructure.

1. Introduction

Urban hydrological infrastructure plays a critical role in managing water resources within densely populated areas. It comprises a complex network of systems, including stormwater drainage, wastewater treatment, water supply networks, and flood control measures (Fletcher *et al.,* 2024). These systems are designed to ensure the sustainable and equitable distribution of water resources while mitigating the risks associated with water scarcity, flooding, and pollution. However, urban hydrological infrastructure faces unprecedented challenges in the 21st century. Aliu et al., (2024) and Ebekozien et al., (2024) highlight that climate change intensifies extreme weather events, resulting in more frequent and severe droughts, floods, and heatwaves. Rising global temperatures exacerbate water scarcity issues, while increased precipitation in some regions contributes to more frequent and intense flooding events (Otto *et al.,* 2023). Urbanization compounds these challenges as land-use changes and the proliferation of impervious surfaces disrupt natural hydrological processes, leading to increased runoff, reduced infiltration, and heightened flood risks (Abraham *et al.,* 2023; Neog *et al.,* 2024; Soori *et al.,* 2024).

Additionally, aging infrastructure, inadequate maintenance, and rapid population growth strain existing urban water systems (Abera, 2022). Moreover, many cities in both developed and developing countries struggle to meet rising water demands while addressing issues related to aging infrastructure, pollution, and the adverse effects of climate change. These interrelated challenges underscore the urgent need for innovative and sustainable solutions to ensure urban water systems' long-term resilience and sustainability. Advancing the integration of emerging technologies, such as artificial intelligence (AI), could provide transformative approaches to address these issues and enhance the management of urban hydrological infrastructure.

According to Shahin *et al.,* (2024) and Sharifi *et al.,* (2024), AI encompasses a wide range of computer-based disciplines focused on creating intelligent systems capable of performing tasks traditionally carried out by humans. In water resources management, AI has made notable advancements, mainly through the adoption of sophisticated models such as Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), Decision Trees (DTs), Random Forests (RFs), Gradient Boosting Machines (GBMs), and hybrid methodologies (Ye *et al.,* 2021; Samadi, 2022; Soori *et al.,* 2024). Early applications of ANNs were crucial in improving river flow predictions, particularly in areas with limited historical data (Yang *et al.,* 2019). These networks excelled at identifying complex, nonlinear relationships between climatic inputs and hydrological outputs, paving the way for broader AI utilization in water management. As challenges in hydrology grew more intricate, techniques such as SVMs and fuzzy logic systems became indispensable (Zhu *et al.,* 2022). These methods effectively addressed uncertainties like fluctuating rainfall patterns and varying soil moisture levels, scenarios where traditional models often struggled due to limited or inconsistent data. AI's capacity to handle large datasets and predict extreme meteorological events, including floods and droughts, has significantly enhanced disaster preparedness. For example, in the Mississippi River Basin, USA, Ganges-Brahmaputra-Meghna Basin, South Asia, and several others, AI-driven flood risk prediction and mitigation strategies have been instrumental in enhancing early warning systems, optimizing resource allocation and improving the resilience of vulnerable communities against extreme hydrological events. Similarly, AI models have demonstrated exceptional efficacy in groundwater management in regions facing water scarcity. These models help forecast groundwater levels and recharge rates, promoting more sustainable resource utilization.

Furthermore, AI has revolutionized water quality management by enabling real-time monitoring and contaminant assessment, as seen in the Ganges River in India, the Mississippi River in the USA, the Danube River in Europe, the Mekong River in Southeast Asia, and the Nile River in Africa. These systems have significantly improved the ability to track pollution sources, assess turbidity levels, and monitor ecosystem health. AI-powered Smart Microclimate Control Systems (SMCS) have transformed resource management in the agricultural sector. By optimizing factors such as temperature, humidity, and soil moisture, these systems have boosted crop yields while improving water-use efficiency (Haider *et al.,* 2024). These diverse applications highlight AI's critical role in addressing the multidimensional challenges posed by climate change, growing water demands, and environmental variability.

In light of its potential, this review seeks to explore the growing role of AI in managing urban hydrological infrastructure through a qualitative approach, providing an in-depth understanding of the subject via detailed analysis of secondary data. Furthermore, the study offers practical insights and recommendations based on its findings. Ultimately, this research contributes to the expanding discourse on integrating advanced technologies into urban water systems, paving the way for more adaptive and sustainable infrastructure to meet the demands of a rapidly changing world.

2. Review of Existing Studies

2.1. Historical Overview of AI Applications in Urban Hydrological Infrastructure

The use of AI in urban hydrological infrastructure started in the early 1980s, coinciding with advancements in computational power and the development of early machine learning algorithms. During this period, AI applications primarily focused on rule-based and expert systems to simulate water flow and predict hydrological behavior. For instance, researchers utilized these systems to simulate rainfall-runoff processes, allowing urban planners to predict flood risks in specific regions. These rule-based systems were limited in scalability and adaptability but marked the initial steps toward automating complex hydrological computations (Maisonobe, 2022). By the late 1980s, Artificial Neural Networks (ANNs) emerged as a groundbreaking AI tool. Early applications of ANNs aimed to improve hydrological forecasting by capturing nonlinear relationships between climatic variables and water flow dynamics. In urban contexts, ANNs were applied to model stormwater drainage systems, providing more accurate predictions of flood events in cities. This period also witnessed the integration of AI with Geographic Information Systems (GIS), enabling spatial analysis of urban hydrological systems to better understand drainage patterns and areas prone to flooding (Zhao *et al.,* 2021).

The mid-1990s marked a significant expansion in the scope of AI applications in urban hydrology, driven by advancements in computing and data availability. During this time, Support Vector Machines (SVMs) and Fuzzy Logic systems were introduced to manage the uncertainties inherent in hydrological data (Yang *et al.,* 2019). These AI models enhanced the accuracy of flood prediction, groundwater recharge estimation, and pollutant transport modeling. For instance, SVMs were employed in urban areas to predict the impacts of heavy rainfall on stormwater systems, offering insights into flood mitigation strategies. Fuzzy Logic systems became particularly valuable for decision-making in water quality management, allowing for real-time assessment of urban water bodies affected by industrial and domestic pollutants (Maisonobe, 2022). Simultaneously, hybrid AI models combining ANNs, SVMs, and Fuzzy Logic gained traction. These models proved highly effective in managing urban water systems by addressing challenges like the variability of precipitation and the impact of impervious surfaces on runoff. This era also saw increased collaboration between AI and remote sensing technologies, which enhanced urban hydrological data collection and analysis (Fletcher *et al.,* 2024).

The 2010 era paved the way for a new era of AI applications characterized by the rise of big data and advanced machine learning techniques. With the proliferation of sensors and IoT devices, urban areas began generating vast amounts of real-time hydrological data, enabling the application of sophisticated AI models. Gradient Boosting Machines (GBMs), Random Forests (RFs), and Deep Learning models emerged as dominant tools during this period. These models handled large, high-dimensional datasets, allowing for improved flood forecasting, water demand prediction, and stormwater management. Deep Learning models, such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), were used for time-series analysis of rainfall and river flow patterns, enabling urban planners to make more informed decisions (Panahi *et al.,* 2021). One notable advancement was the integration of AI with smart water grid systems, which utilized real-time data from sensors installed in urban water distribution networks to optimize water allocation, detect leaks, and monitor water quality (Maisonobe, 2022). In the 2020s, the focus has shifted toward sustainability and resilience as climate change and rapid urbanization have intensified challenges such as water scarcity, flooding, and infrastructure aging. To address these issues, AI-driven solutions are increasingly being used for adaptive water management and disaster preparedness. Presently, AI models now incorporate Nature-based Solutions (NbS) to design urban landscapes that mitigate flood risks while promoting biodiversity (Aghimien *et al.,* 2024). For example, AI algorithms are used to model the effectiveness of green roofs, permeable pavements, and urban wetlands in managing stormwater runoff. Furthermore, AI has been instrumental in advancing the circular economy of water. By predicting wastewater composition and optimizing its treatment, AI enables the recovery of resources such as nutrients and energy, contributing to sustainable urban water management (Zhu *et al.,* 2022). Table 1 summarizes the evolutionary milestones of AI in urban hydrological infrastructure.

Table 1. Evolutionary Milestones of AI in Urban Hydrological Infrastructure

Period	Key milestone
The early 1980s	The use of rule-based and expert systems for hydrological modeling began, marking the initial steps toward automating complex hydrological computations.
The late 1980s	ANNs emerged as a significant tool for improving hydrological forecasting and modeling stormwater drainage systems.
Mid-1990s	The introduction of SVMs and Fuzzy Logic systems helped manage uncertainties in hydrological data, enhancing flood prediction and water quality management.
The 2010s	The rise of big data and advanced machine learning techniques, including Gradient Boosting Machines (GBMs), Random Forests (RFs), and Deep Learning models, improved real-time analysis and decision-making in urban water management.
The 2020s	AI-driven solutions have increasingly focused on sustainability and resilience, incorporating NbS and advancing the circular economy of water.

2.2. Challenges in Urban Hydrological Infrastructure and the Role of AI

One of the most pressing issues is aging infrastructure. In many urban areas, particularly in developing nations, water distribution networks, drainage systems, and treatment facilities have surpassed their designed lifespans (Ferreira *et al.,* 2022). These systems suffer from inefficiencies such as leaks, contamination, and reduced capacity to handle current demands. Also, AI-driven predictive maintenance systems are revolutionizing this space by analyzing sensor data to detect early signs of wear or potential failures (Otto *et al.,* 2023). Machine learning models can also forecast pipeline bursts or drainage blockages, allowing cities to proactively address issues, minimize disruptions, and extend the lifespan of their infrastructure. Urbanization further exacerbates these challenges. As cities expand, water demand increases and the increase in impervious surfaces (such as concrete and asphalt) leads to higher runoff, reduced groundwater recharge, and increased flood risks (Pokhrel *et al.,* 2022). AI offers a solution by simulating water flow and modeling the impact of urban development on existing hydrological systems. These tools use geospatial data and advanced algorithms to identify areas prone to flooding or water scarcity, helping urban planners design more resilient and adaptive infrastructure (Ferreira *et al.,* 2022).

Climate change compounds these problems by intensifying extreme weather events, including floods and droughts (Sharifi *et al.,* 2024). As such, urban hydrological systems are often overwhelmed by heavy rainfall or strained by prolonged dry spells, with traditional models failing to predict the increasing variability of climatic conditions. AI excels in processing large datasets from weather stations, satellites, and historical records to provide accurate forecasts and risk assessments (Zhu *et al.,* 2022). AI-driven flood prediction models, for example, integrate meteorological data with real-time hydrological measurements, enabling early warning systems that save lives and reduce economic losses. Water quality management is another significant challenge in urban areas, where industrial discharges, untreated sewage, and runoff pollute water bodies. Traditional water quality monitoring methods rely on extensive manual sampling, which is time-consuming and often ineffective in detecting real-time contamination (Saheb *et al.,* 2019). AI-powered monitoring systems use sensors and machine learning algorithms to instantly analyze water parameters like turbidity, pH, and contaminant levels. These systems help authorities identify pollution sources, assess ecosystem health, and ensure safe and sustainable water supplies (Ferreira *et al.,* 2022). However, adopting AI solutions is not without its challenges. Many cities cannot afford the infrastructure or skilled workforce required to deploy and maintain AI technologies (Haider *et al.,* 2024). Researchers focus on developing cost-effective AI tools to overcome resource-constrained challenges. Cloud-based platforms and open-source machine learning frameworks are making AI more accessible and reducing the financial and technical hurdles to adoption.

3. Research Methodology

This review aims to explore the growing role of Artificial Intelligence (AI) in the management of urban hydrological infrastructure. The review was achieved using a qualitative approach, which allows for an in-depth understanding of the subject through detailed secondary data analysis. According to Byrd (2020), qualitative research is a method designed to explore and understand phenomena within their natural context. As part of the qualitative approach, this study employed a systematic literature review to ensure a deep understanding of the existing body of knowledge.

Systematic literature reviews align with the principles of qualitative research by enabling a structured and transparent process for synthesizing information from diverse sources (Rathnayaka *et al.,* 2022). Some steps involved in conducting a systematic literature review include identifying, selecting, evaluating, and synthesizing relevant research from academic databases, journals, conference proceedings, and other scholarly sources. This process typically begins with formulating clear research questions or objectives, followed by developing a detailed search strategy to locate relevant studies. To ensure transparency and reproducibility, these reviews adhere to a structured approach guided by predefined criteria and protocols for screening, inclusion, exclusion, and data extraction. Finally, the synthesized findings are analyzed and reported in a manner that provides insights into the research topic. A quantitative approach was also employed to strengthen the study and provide a broader perspective. The quantitative analysis was achieved via a bibliometric analysis method, which systematically evaluates the scholarly literature using quantitative metrics to analyze trends, patterns, and networks within the research field (Sajovic and Boh Podgornik, 2022).

VOSviewer software is a widely recognized tool for visualizing and analyzing bibliographic data. According to Zhao *et al.,* (2021), and was thus adopted in this study. The search strategy focused on identifying relevant studies by targeting titles, abstracts, and keywords to ensure a holistic capture of relevant literature. The final search string employed was (TITLE-ABS-KEY) ("urban hydrology" OR "artificial intelligence" OR "machine learning" OR "water management" OR "extreme events" OR "flood prediction") AND (PUBYEAR > 2010 AND PUBYEAR < 2024) AND (LIMIT-TO [SUBJAREA, "ENGI", "ENV", "COMP", "AGRI", "EART", "SSCI"]) AND (LIMIT-TO [DOCTYPE, "j"] OR LIMIT-TO [DOCTYPE, "cp"]) AND (LIMIT-TO [LANGUAGE, "English"]). Subject areas included "ENGI" (Engineering), "ENV" (Environmental Science), "COMP" (Computer Science), "AGRI" (Agricultural Science), "EART" (Earth and Planetary Sciences), and "SSCI" (Social Sciences). The Scopus database was assessed for this study due to its extensive coverage of peer-reviewed literature, multidisciplinary scope, and advanced tools for bibliometric analysis. Document types were restricted to journals (j) and conference proceedings (cp). The study considered publications from 2010 to 2024 to ensure the results reflected recent advancements. The search, conducted in late December 2024, resulted in bibliometric data downloaded in comma-separated values (CSV) format, yielding 2,098 documents.

4. Results and Discussion

4.1. Document Types and Distribution

The bibliometric analysis of the 2,098 documents revealed significant trends and patterns. These documents were classified into two primary categories: journal articles and conference papers. As illustrated in Figure 1, journal articles accounted for 71% of the total publications, while conference papers comprised the remaining 29%. This distribution highlights the prominence of peer-reviewed journal articles in advancing research within this field, although conference proceedings serve as a critical platform for disseminating emerging findings and fostering collaborations.

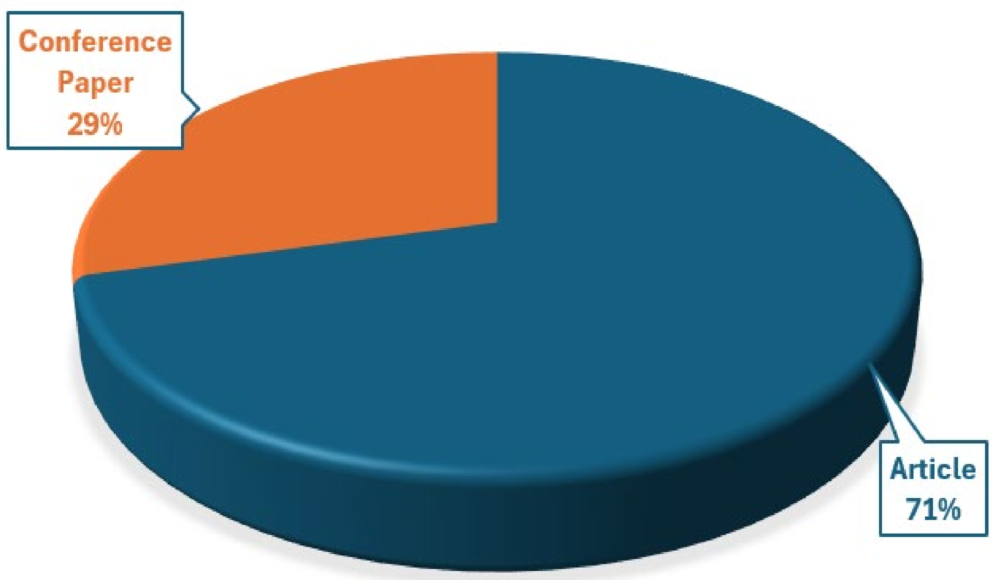

Figure 1: Documents by type

4.2. Analysis of Co-occurrence of Keywords

A co-occurrence map was created to analyze the frequency and relationships of keywords based on the bibliographic data collected for the study. These keywords were extracted from the titles, abstracts, and keyword sections of the articles reviewed. While VOSviewer typically uses a default ranging co-occurrence threshold of five keywords, various studies have adopted different thresholds, from two (Baier-Fuentes *et al.,* 2018) to as many as 40 (Saheb et al., 2019). For this study, a minimum threshold of four co-occurrences was selected to ensure a balance between obtaining widespread results and avoiding redundant keywords. The analysis revealed 8,485 keywords across 2,098 articles, with 565 keywords meeting the threshold of four co-occurrences. According to Van Eck and Waltman (2013), the proximity of keywords in the map indicates their frequency of co-occurrence, with larger nodes representing more frequently occurring keywords. The network visualization map in Figure 2 shows the five distinct clusters of co-occurring keywords related to AI in urban hydrological infrastructure. The lines connecting the nodes reflect the strength of their relationships, with thicker lines representing stronger co-occurrence connections.

Cluster 1: AI in Flood Prediction and Early Warning Systems

The red cluster focuses on AI applications in flood prediction and early warning systems, a critical component of urban hydrological resilience. Key terms such as "floods," "forecasting," "streamflow," "runoff," and "numerical model" highlight AI's role in advancing predictive accuracy. Flood events are becoming more frequent and severe due to climate change, requiring innovative solutions to improve forecasting and minimize damage. AI techniques, including machine learning (ML) models like artificial neural networks (ANNs), support vector machines (SVMs), and decision trees, have been widely adopted for hydrological predictions. For instance, a study by Albahri *et al.,* (2024) employed ANNs to predict river discharge levels with unprecedented accuracy, enabling authorities to prepare for and respond to flooding effectively. Deep learning models, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), have further enhanced flood forecasting (Panahi *et al.,* 2021). These models can process large datasets, including historical rainfall patterns, real-time meteorological data, and topographical maps, to provide more reliable predictions. Research by Yang *et al. (2019) demonstrated that using RNNs in real-time streamflow forecasting significantly improves* the lead time for early warnings. Moreover, integrating AI with Internet of Things (IoT) devices such as water level sensors and weather stations allows for continuous data collection and analysis, enabling authorities to monitor conditions in real time. For example, the FloodAI project developed a system that combines IoT data with AI algorithms to provide real-time flood risk alerts, reducing response times and enhancing community preparedness (Abraham *et al.,* 2023).

Additionally, AI-driven simulations have enabled researchers to model complex hydrological interactions, such as rainfall-runoff processes and river flow dynamics (Albahri *et al.,* 2024). Studies like those by Yang *et al.,* (2019) also highlight how AI models outperform traditional hydrological models in handling nonlinear and chaotic water systems. This capability is crucial for urban areas where multiple variables, including impervious surfaces and aging infrastructure, exacerbate flood risks. By integrating predictive modeling with early warning systems, AI empowers urban planners and policymakers to implement proactive measures, such as evacuations, resource allocation, and structural adaptations. The red cluster, therefore, emphasizes the transformative potential of AI in mitigating flood impacts and safeguarding urban communities.

Cluster 2: AI in Urban Water Demand Forecasting

The green cluster represents AI's application in urban water demand forecasting, as highlighted by keywords like "water use," "decision support systems," and "resource management." Accurate forecasting is vital for sustainable water resource allocation in rapidly urbanizing regions. According to Shahin *et al.,* (2024), traditional forecasting methods often fall short of accounting for the variability introduced by population growth, climate change, and urban development. Conversely, AI leverages advanced algorithms to analyze historical data and predict future water demand with relatively higher precision. For instance, Mu et al., (2020) utilized long short-term memory (LSTM) networks to forecast water demand in urban areas, demonstrating a significant reduction in prediction errors compared to conventional methods. Similarly, decision support systems (DSS) powered by AI have been implemented to optimize water supply networks. Research by Soori *et al.,* (2024) showed how AI-enabled DSS could dynamically adjust water allocation to meet fluctuating demands, minimizing wastage and enhancing reliability. AI has also been applied to develop predictive maintenance strategies for water infrastructure, ensuring that leaks and inefficiencies are addressed before they escalate.

Furthermore, AI-based models are instrumental in scenario planning, allowing urban planners to simulate various demand scenarios under different conditions, such as droughts or rapid urbanization (Soori *et al.,* 2024). Such advancements have practical implications for cities facing water scarcity. AI enhances the efficiency of water supply systems and supports sustainable development goals by helping promote equitable resource distribution. The green cluster highlights the indispensable role of AI in ensuring the long-term sustainability of water resources.

Cluster 3: AI in Real-Time Monitoring of Water Quality

The blue cluster emphasizes AI's role in real-time water quality monitoring, as evident from keywords such as "water quality," "wastewater treatment," and "water pollution." Ensuring the safety and quality of urban water supplies is a growing challenge, particularly in regions grappling with industrial pollution and aging infrastructure (Pokhrel *et al.,* 2022). Thus, AI technologies have revolutionized water quality monitoring by enabling the rapid detection of contaminants and optimizing wastewater treatment processes. Machine learning algorithms have been widely applied to analyze sensor data and classify water pollutants. Zhu *et al.,* (2022) demonstrated the use of support vector machines (SVMs) in identifying water contaminants with high accuracy. This approach reduces the reliance on labor-intensive and time-consuming laboratory tests, enabling faster decision-making. Deep learning models, such as CNNs, have also been employed to process remote sensing data for large-scale water quality assessment. AI-powered wastewater treatment systems have also been developed to optimize treatment processes. These systems adjust operational parameters, such as aeration rates and chemical dosages, based on real-time data, improving efficiency and reducing costs (Sakkaravarthy *et al.,* 2024). For example, Aquaai Corporation, an AI-based platform based in California, leverages ML algorithms to monitor and manage wastewater treatment plants, ensuring compliance with regulatory standards (Reference). By integrating AI with IoT and cloud computing, real-time monitoring systems can provide actionable insights to utilities and regulators. This enables proactive interventions, such as issuing advisories or implementing stricter pollution controls. The blue cluster thus highlights AI's potential to enhance the safety, efficiency and sustainability of urban water systems.

Cluster 4: AI in Optimization of Stormwater Management Systems

The yellow cluster highlights AI's transformative potential in optimizing stormwater management systems, a critical aspect of mitigating urban flooding, reducing water pollution, and enhancing the resilience of drainage infrastructure. The presence of keywords such as "stormwater management," "optimization," "drainage infrastructure," and "urban flooding" underscores this focus. As urbanization and climate change increase the frequency and intensity of extreme weather events, effective stormwater management has become a top priority for cities worldwide (Panahi *et al.,* 2021). AI offers innovative tools to optimize these systems, driving improvements in their efficiency, adaptability, and sustainability. One of the significant applications of AI in stormwater management is predictive modeling. AI algorithms such as ANNs, LSTM networks, and SVMs can analyze vast datasets, including historical rainfall patterns, land use maps, and soil permeability, to predict stormwater runoff peak discharge and volume (Yang *et al.,* 2019). These models outperform traditional hydrological models in accuracy and computational efficiency. For instance, a study by Cea and Costabile (2022) demonstrated that AI-based systems could predict runoff more effectively under complex urban conditions, enabling planners to better design drainage systems that mitigate flood risks. Another critical use of AI is real-time monitoring and optimization of stormwater systems. Internet of Things (IoT) sensors embedded in stormwater infrastructure collect data on water flow, sediment levels, and equipment performance. AI algorithms process this data to detect anomalies, such as blockages or equipment failures, and recommend timely interventions. AI also contributes to sustainable stormwater management by optimizing the design and placement of green infrastructure (GI) solutions like rain gardens, bioswales, and permeable pavements (Sharifi *et al.,* 2024). Using geospatial data and hydrological models, AI tools identify optimal locations for GI installations, maximizing water infiltration and pollutant filtration while minimizing costs. Pokhrel *et al.,* (2022) demonstrated how AI-driven planning tools increased the efficiency of GI projects, significantly reducing urban flooding and improving water quality.

Furthermore, AI enables cities to integrate long-term climate change scenarios into stormwater planning. Adaptive management strategies, supported by AI, can evaluate the impact of changing rainfall patterns and rising temperatures on stormwater systems and recommend infrastructure upgrades to maintain their effectiveness. For example, research by Labonnote (2024) showcased how AI could model climate change impacts, helping cities future-proof their stormwater management systems. Therefore, the yellow cluster underscores AI's versatile role in stormwater management, from predictive analytics and operational optimization to sustainability and public engagement.

Cluster 5: AI in Urban Flood Risk Assessment and Mapping

The purple cluster represents the application of AI in urban flood risk assessment and mapping, a crucial area of study for mitigating the impacts of urban flooding on infrastructure, communities and ecosystems. Centered on keywords like "risk assessment," "groundwater," and "mapping," this cluster emphasizes the role of AI in evaluating urban flood risks and generating detailed, data-driven maps to guide urban planning and disaster preparedness strategies. Flood risk assessment involves evaluating both hazard exposure and the vulnerabilities of urban areas. AI enables more accurate and dynamic assessments by analyzing extensive datasets, including topography, hydrology, rainfall patterns, land use, and socioeconomic indicators (Cea and Costabile, 2022). Machine learning algorithms, such as Random Forest (RF) and Gradient Boosting Machines (GBM), are particularly effective in identifying flood-prone areas. Studies like that of Neog *et al.,* (2024) highlight how these algorithms outperform traditional statistical methods in flood risk classification, providing more granular insights into the factors driving urban flooding. Integrating remote sensing data is one key advancement AI brings to flood risk mapping. When coupled with AI, high-resolution satellite imagery and LiDAR data allow for the creation of precise flood maps.

Deep learning models like CNNs can analyze spatial data to detect features like riverbanks, floodplains, and impervious surfaces. For example, a study by Panahi *et al.,* (2021) determined the use of CNNs to map flood extents with unparalleled accuracy, supporting emergency response and long-term planning. AI also enhances real-time flood monitoring and forecasting, which are essential risk mitigation components. AI algorithms can accurately predict flood events by processing data from IoT sensors, weather stations, and social media feeds. For instance, Samadi (2022) explored how AI-driven predictive systems integrated real-time hydrological data to issue timely warnings, reducing human and economic losses during urban flood events.

Additionally, AI facilitates the creation of dynamic flood vulnerability indices by incorporating socioeconomic data, such as population density, infrastructure resilience, and access to emergency services (Ye, 2021). This multidimensional approach helps urban planners prioritize interventions and allocate resources more effectively. Finally, research by Dixon *et al.,* (2021) showcased how AI-based models identified high-risk zones, aiding in targeted urban flood mitigation strategies.

Therefore, the purple cluster stresses the versatility and power of AI in transforming urban flood risk assessment and mapping.

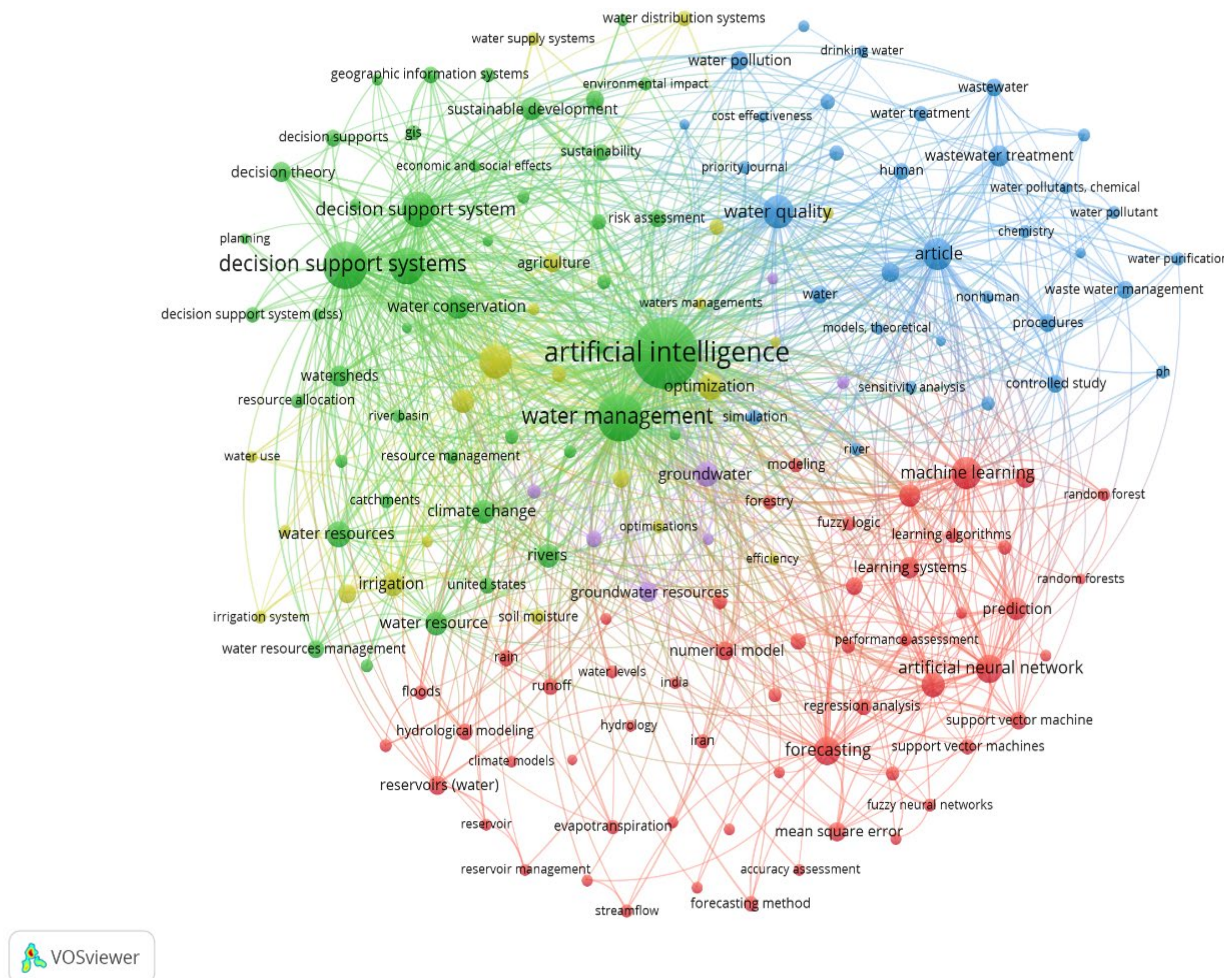

Figure 2: Overlay visualization map for co-occurring keywords

5. Practical Applicability of the Findings

This study's findings highlight AI's transformative potential in urban water and flood management systems, presenting significant opportunities for private industry professionals across various sectors, including construction, engineering, technology, and urban planning.

One of the key findings from this study is the critical role AI plays in flood prediction and early warning systems. The ability to predict floods with greater accuracy allows cities to take proactive measures, such as reinforcing vulnerable infrastructure, implementing flood barriers, or ensuring timely evacuations. For professionals, AI-based flood prediction models provide valuable data to inform infrastructure design, resource allocation, and adaptive strategies. The study emphasizes that by integrating AI with IoT devices, such as water level sensors and weather stations, real-time data collection can be significantly enhanced, leading to more effective flood management. Companies may consider leveraging these technologies to improve flood preparedness and response strategies. For example, AI-driven predictive flood models, like those used by NOAA and the FloodAI project, can be implemented by private sector organizations to improve flood risk management and reduce disaster-related losses. Also, engaging with local governments and utilities to promote the widespread adoption of these technologies could have far-reaching benefits in terms of cost savings and enhanced public safety.

Another important finding from the study is AI's potential to optimize water demand forecasting, a critical component of sustainable water management. AI-based forecasting models enable utilities and infrastructure sectors to allocate resources better, reduce waste, and improve operational efficiency. Therefore, private industry professionals in water utilities and infrastructure may prioritize the integration of AI into water demand forecasting processes, enabling them to create smart water management systems that can dynamically adjust water distribution based on real-time demand forecasts, ultimately improving sustainability and reducing costs. Additionally, they may consider collaborating with AI technology providers to develop tailored solutions that meet the specific needs of their water systems. Companies that adopt AI-driven water demand forecasting will be better positioned to address future challenges related to population growth, climate change, and urbanization.

The study also highlights the value of AI in real-time water quality monitoring, a crucial application for ensuring safe and clean water supplies. The ability to monitor water quality in real time allows for the rapid detection of contaminants, thereby improving regulatory compliance and reducing the reliance on traditional, time-consuming laboratory tests. AI-powered systems can detect pollutants and optimize water treatment processes, ensuring water quality remains within safe limits. Companies like Aquaai and IBM's Green Horizons are already using AI for water quality monitoring, demonstrating the potential benefits of these systems for water utilities and industrial sectors. Therefore, private sector professionals involved in water utilities and environmental monitoring should prioritize the implementation of AI-driven water quality monitoring technologies to ensure better water safety and efficiency. By implementing AI systems, these companies can improve the speed and accuracy of water quality assessments and treatment adjustments, ultimately leading to more efficient and sustainable water management practices.

In addition, the study emphasizes the role of AI in optimizing stormwater management systems. As urbanization and extreme weather events increase, the risk of urban flooding becomes more pressing, making efficient stormwater infrastructure essential. AI models, such as ANNs LSTM networks, can process vast amounts of environmental data to predict stormwater runoff and optimize drainage system performance. Cities like Philadelphia and Seattle have already demonstrated the effectiveness of AI in stormwater management, and private companies can learn from these examples to improve their stormwater systems. Based on the study's findings, a recommendation is for private sector professionals to adopt AI technologies for stormwater management. By doing so, they can optimize drainage systems and integrate green infrastructure solutions, which are increasingly recognized for their effectiveness in managing stormwater and improving urban resilience to climate change. Companies should also consider investing in AI-driven models to forecast runoff and optimize stormwater systems, ensuring that urban areas are better equipped to handle extreme weather events.

Finally, the study highlights AI's value in urban flood risk assessment and mapping. AI models can process large datasets from remote sensing technologies, such as satellite imagery and LiDAR, to create highly accurate and detailed flood risk maps. These maps are essential for identifying flood-prone areas, prioritizing mitigation efforts, and designing flood-resistant infrastructure. Private industry professionals in urban planning and infrastructure design can benefit from AI-based flood risk assessment tools by using them to improve resource allocation and inform flood mitigation strategies. Collaborating with governmental agencies to enhance the accuracy of flood hazard maps can also improve disaster preparedness efforts and contribute to more sustainable urban development.

6. Conclusions and Areas of Future Studies

The integration of AI into urban hydrological infrastructure has gained significant traction over the past decade, driven by the increasing demand for smarter and more efficient water management systems in cities. With the growing challenges of climate change, rapid urbanization, and water scarcity, there is an urgent need for innovative solutions that can optimize water resource use, reduce flooding risks, and ensure the safety and sustainability of urban environments. AI, with its ability to analyze large datasets, make accurate predictions, and automate decision-making processes, offers tremendous potential to address complex challenges in urban water management. A systematic review approach, supported by bibliometric studies, revealed 2,098 documents from 2010 to date on AI's role in urban water management, underscoring the growing interest and potential for innovation in this field. These studies highlight the transformative impact AI could have in enhancing the efficiency and resilience of urban water systems. Overall, this study uncovered that five clusters of AI applications have emerged within this domain. These include AI in flood prediction and early warning systems, AI in urban water demand forecasting, AI in real-time monitoring of water quality, AI in optimization of stormwater management systems, and AI in urban flood risk assessment and mapping. These clusters represent key areas where AI is making a significant impact, contributing to more sustainable, responsive, and resilient urban water management practices.

Practically, these insights provide valuable direction for industry professionals and policymakers aiming to integrate AI into urban hydrological infrastructure. The emergence of AI in flood prediction, water demand forecasting, stormwater management, water quality monitoring, and flood risk assessment indicates a clear shift toward more data-driven, efficient, and proactive approaches in managing urban water systems. These findings suggest that AI can play a pivotal role in enhancing decision-making processes, reducing operational risks, and improving resource allocation within these sectors. For urban planners, engineers, and other stakeholders, the application of AI offers an opportunity to modernize existing infrastructure, making it more resilient to the growing challenges posed by climate change and urbanization. Furthermore, AI's potential for optimizing resource use, improving sustainability, and mitigating flood risks can help cities better prepare for extreme weather events while ensuring the continued provision of essential water services. As AI technology continues to evolve, future studies should focus on refining these AI applications, enhancing their integration with other technologies such as IoT and big data analytics, and evaluating their long-term impact on urban resilience. Moreover, there is a need for collaboration between academia, industry, and government agencies to ensure the widespread adoption and effective implementation of these technologies, which will ultimately contribute to more sustainable and adaptive urban water management systems.

Despite the contributions of this study, several limitations must be acknowledged. First, the reliance on bibliometric data, while comprehensive, may not capture the full spectrum of AI applications in urban hydrological infrastructure, particularly those emerging in newer or less-publicized studies. The documents analyzed may also reflect a concentration of research in specific regions or institutions, potentially overlooking advancements in AI applications from other areas or industries. Future studies might want to empirically investigate AI applications through case studies, field experiments, or surveys to provide a deeper understanding of the global adoption and deployment of these technologies. Additionally, while the study focuses on the major clusters of AI applications, it does not explore in-depth the specific challenges or barriers faced by professionals when attempting to implement these technologies in real-world urban settings. Factors such as cost, data privacy concerns, and the need for specialized expertise may hinder the widespread adoption of AI but were not extensively examined in this review. Future research could consider examining case studies or conducting interviews with industry professionals to identify these practical challenges and provide more context to the findings.

Declaration of Competing Interest

The author declares that I have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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