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Sustainable Water Management in Smart Cities: A Systematic Review of Digital and Green Technologies

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ABSTRACT

Water-related issues in cities have gotten worse due to rapid urbanization, climate variability, and ageing infrastructure, calling for creative and sustainable management techniques. The purpose of this study is to discuss the integration of digital technologies and green infrastructure in smart cities for better management of sustainable water resources in cities. The aim of this review is to critically deliberate and evaluate the potential of emerging technologies such as Internet of Things (IoT) sensors, big data analytics, Artificial Intelligence (AI), cloud computing, GIS, and digital twins in synergistic integration with green infrastructure such as green roofs, bioswales, permeable pavements, and constructed wetlands. Using popular scientific databases like Scopus, Web of Science, ScienceDirect, and Google Scholar, a systematic literature review was carried out in accordance with the PRISMA framework. Keywords pertaining to smart water management, IoT-based monitoring, digital water technologies, and green infrastructure were used to find pertinent articles published between 2008 and 2025. These articles were then screened for relevance, language, and citation impact. The results show that emerging technologies are effective in improving real-time monitoring, predictive maintenance, leakage detection, demand forecasting, and decision-support systems, whereas green infrastructure is effective in stormwater management, groundwater recharge, urban cooling, and climate resilience. The integration of hybrid systems is more efficient in improving system efficiency, reducing non-revenue water, improving flood mitigation, and enhancing water circularity in cities. Overall, this integration of digital innovation and ecological design offers a transformative potential for resilient, adaptive, and sustainable urban water systems in smart cities.

Introduction

Globally, cities are changing due to rapid urbanization, which is causing notable increases in resource consumption, infrastructure demand, and population density. As cities struggle to meet the growing demands for drinking water, sanitation, industrial use, and environmental protection, water stands at the forefront of urban challenges among essential resources (Sun *et al.*, 2015.) Natural landscapes are replaced by impermeable surfaces as urban areas grow, increasing stormwater runoff, decreasing groundwater recharge, and increasing the risk of flooding. Concerns about water scarcity, deteriorating water quality, and the general resilience of urban water systems are exacerbated by ageing water infrastructure, climate variability, and rising consumption (Mohsin, 2024). These demands show how urgently creative solutions are needed to manage water sustainably in quickly expanding cities. Many urban areas are adopting smart city models in response to these issues, which combine cutting-edge technologies with sustainable planning to improve ecological resilience, resource efficiency, and service delivery (Khosla, 2024; Chen, 2024). As cities look for ways to guarantee dependable water supply, effective wastewater treatment, efficient distribution, flood mitigation, and long-term environmental protection, sustainable water management has emerged as a key element of this shift. The demands of the modern world cannot be met by traditional centralized water systems alone. Rather, cities are increasingly using a mix of nature-based solutions and digital tools that provide accuracy and flexibility (Cui *et al.*, 2021).

This review's goal is to investigate how, in the context of smart cities, integrating digital and green technologies can improve sustainable water management. Internet of Things (IoT) sensors,

artificial intelligence, data analytics, smart meters, digital twins, and remote monitoring platforms are examples of digital technologies used in water systems that allow for real-time assessment, predictive maintenance, and optimized operations. These systems facilitate quick access to data, enhance decision-making, and assist in identifying problems like contamination, leaks, or unusual consumption patterns before they become more serious. Green technologies, on the other hand, work with natural processes to improve stormwater management, water quality, restore ecological functions, and increase climate resilience. Examples of these technologies include rain gardens, constructed wetlands, green roofs, bioretention cells, permeable pavements, and other green-blue infrastructure. Green technologies improve sustainability, biodiversity, and environmental benefits while digital technologies improve control and precision (Chandratreya, 2024). In order to develop resilient, effective, and ecologically balanced urban water systems, this review looks at how these two types of technology can be successfully integrated. Examples of integrated applications, developments in digital and green water technologies, an analysis of urban water management issues, and future directions for smart, sustainable cities are all included in the scope. The potential synergies that result from combining nature-based infrastructure with real-time digital monitoring are highlighted, allowing cities to anticipate and prevent water-related issues as well as respond to them.

The review's objectives are to give readers a thorough grasp of how urban water management is changing and to identify areas for innovation that could contribute to a more sustainable urban future. In general, the paper is organized as follows: an introduction to the

difficulties in managing urban water resources; a summary of digital technologies that improve efficiency and monitoring; and a discussion of green technologies that support ecological resilience. After examining integrated strategies that incorporate both natural and technological solutions, it ends with recommendations for future research, policy, and implications for smart city sustainable water management.

Materials and Methods

To find relevant research on sustainable water management in smart cities, a systematic review of the literature was carried out using the PRISMA framework. After eliminating duplicates, 680 articles remained out of the 1020 records that were initially found through database searching. Relevance, English language, and citation impact were used to screen articles published between 2008 and 2025; 388 full-text articles were evaluated for eligibility. Ultimately, 78 extremely pertinent articles were chosen for the quantitative synthesis, and 156 studies were included in the qualitative review. The PRISMA flow diagram shows the comprehensive study selection procedure (Figure 1).

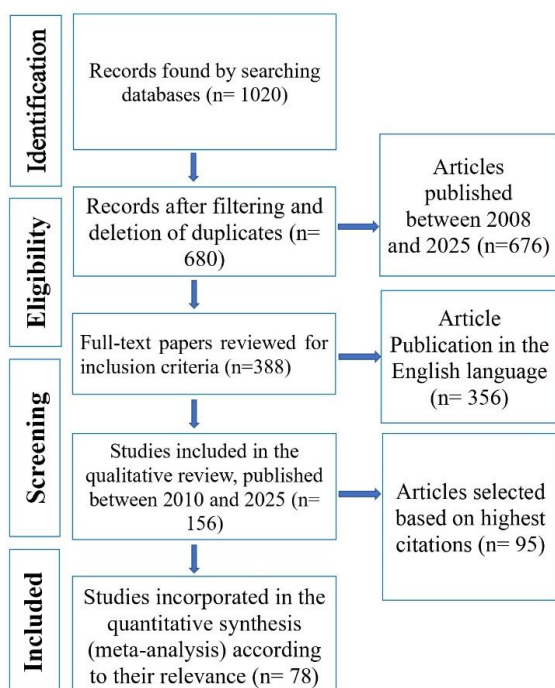


Figure 1. PRISMA Methodology Results and Discussion

3.1 Sustainable Water Management: Definitions, Principles, and Global Relevance- The strategic use, preservation, and restoration of water resources in a way that guarantees sufficient supply, environmental balance, and social equity for current and future generations is known as sustainable water management (Azmi *et al.*, 2024). It is based on a number of fundamental ideas, such as conserving freshwater ecosystems, minimizing pollution, and distributing water services fairly among various urban population segments. Practically speaking, sustainability entails lowering water network losses, safeguarding sources from pollution, increasing wastewater treatment and reuse, encouraging rainwater harvesting, and making sure that water infrastructure is built and maintained to withstand long-term demographic and climatic pressures (Kurunthachalam, 2014; Marsalek, 2011).

In order to achieve sustainability in cities, more regenerative and adaptive water systems must replace conventional linear ones that extract, use, and dispose of water. These systems priorities the efficient use of wastewater, the restoration of natural hydrological cycles, the incorporation of ecological processes into urban planning, and the consistent delivery of drinkable water (Mccall, 2024). Global environmental and development priorities, particularly those expressed in Sustainable Development Goals 6, 11, and 13 are closely aligned with sustainable water management

(Figure 2). SDG 11 emphasizes the necessity of safe and resilient cities, SDG 13 concentrates on climate action, and SDG 6 emphasizes universal access to clean water and sanitation (Baig *et al.*, 2025). By improving resource efficiency, bolstering climate resilience, and guaranteeing fair access to necessary services in quickly growing urban environments, smart, sustainable water systems directly support these objectives.



Figure 2. Sustainable development goals related to sustainable water management

3.2 Smart City Framework and Its Application to Urban Water Systems- A contemporary and increasingly important basis for putting sustainable water management into practice is provided by the smart city framework. To enhance the effectiveness of urban services, a smart city makes use of digital technologies, data-driven decision-making, integrated infrastructure, and citizen participation (Aivazidou *et al.*, 2021; Angelidou *et al.*, 2017). This framework turns conventional water system operations into intelligent networks with automated control, predictive analytics, and real-time monitoring. In order to support early system failure detection, optimize distribution, and lower energy consumption in treatment and pumping processes, smart sensors can continuously measure flow, pressure, leakages, and water quality. These data are then analyzed by sophisticated software platforms (Dai *et al.*, 2025). Beyond efficiency, the smart city model increases resilience by empowering cities to foresee and promptly address water-related hazards like floods, droughts, and infrastructure failures. Planners can assess vulnerabilities, create adaptable strategies to protect water security, and simulate future scenarios using digital twins, remote sensing technologies, and decision-support models (Kapucu *et al.*, 2024). This framework also makes circularity possible because smart technologies make it easier to monitor, treat, and reuse wastewater, creating a closed-loop system that continuously cycles water resources in urban areas. In order to promote responsible water use, citizen engagement is another essential component of smart cities. Residents are empowered to monitor consumption, report problems, and take part in conservation efforts thanks to transparent information provided by smart meters, online dashboards, and mobile applications (Liu *et al.*, 2021). When combined, these components present the smart city strategy as a potent facilitator of sustainable water management. Smart cities develop a comprehensive model that makes water systems more effective, adaptable, resilient, and accessible by fusing digital solutions with ecological and circular practices (Damman *et al.*, 2023). Smart water management is a key component of future sustainable cities because of this integrated vision, which supports long-term sustainability goals while addressing the urgent needs of urban populations.

4.Green Technologies and Nature-Based Solutions for Urban Water Systems

4.1 Types of Green Technologies in Urban Water Management- Ecologically motivated methods of water management in urban settings are provided by green technologies and natural solutions. Permeable pavements, bioswales, constructed wetlands, and green roofs are some of the most popular. Building rooftops with green roofs have vegetation layers that collect rainfall, lessen runoff, and offer thermal insulation (Monteiro *et al.*, 2023) (Figure 3). By

treating wastewater and stormwater using soil, plants, and microbial processes, constructed wetlands replicate the functions of natural wetlands and frequently produce high-quality effluent fit for non-potable reuse (Srivastava *et al.*, 2022). Shallow, vegetated channels called bioswales improve filtration, slow down stormwater flow, and encourage the removal of pollutants and sediments. By replacing traditional impervious surfaces with materials that let rainfall seep into the ground, permeable pavements lower surface runoff, lessen flooding, and promote aquifer recharge (Lee, 2019). When combined, these technologies aid in the restoration of natural hydrological processes in densely populated areas. They lessen the strain on traditional drainage systems and enhance overall water cycle stability in cities by permitting water to seep in, evapotranspiration, or be momentarily retained (Mccall, 2024). Along with increasing the aesthetic and recreational value of urban areas, they also improve biodiversity by establishing habitats for plants, insects, and birds.

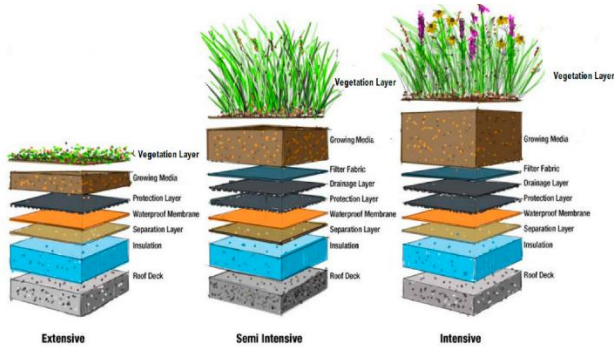


Figure 3. Different types of green roofs and their layers (Monteiro *et al.*, 2023)

4.2 Functional Contributions to Stormwater Management and Climate Adaptation

Urban cooling, groundwater recharge, and stormwater management all heavily rely on natural solutions. Green roofs and bioswales serve as vital buffers that absorb rainfall, postpone peak flow, and lessen the chance of flooding during strong storms in densely populated areas where impermeable surfaces predominate (Gonzalez-Meler *et al.*, 2013). These purposes are further enhanced by constructed wetlands and permeable pavements, which allow water to seep into the ground and replenish groundwater supplies that are frequently exhausted by urban extraction. In order to preserve ecological health and guarantee sustainable water availability, this natural recharge process is essential (Pessoa, 2025). Another important advantage of green infrastructure is urban cooling. Through evapotranspiration, vegetated systems release moisture into the atmosphere, lowering surface temperatures and lessening the impact of the urban heat island. Wetlands and green roofs can improve thermal comfort and lower energy consumption for cooling by lowering ambient temperatures in their immediate surroundings. With cities becoming more susceptible to heatwaves and temperature extremes, these cooling effects are especially crucial for climate adaptation strategies (Kumar *et al.*, 2024). Sustainable water reuse is also supported by green technologies. Cities can develop multipurpose water systems that ease the strain on centralized supplies by combining rainwater harvesting and greywater recycling systems with green roofs, wetlands, and bioswales. For instance, rainwater collected from rooftops can be filtered in bioswales or wetlands before being used for irrigation or non-potable household uses. In a similar manner, constructed wetlands can be used to treat household greywater before it is used again, helping to create a closed-loop urban water cycle (Rodrigues *et al.*, 2023).

4.3 Global Case Examples of Successful Implementation

The revolutionary potential of green technologies in water management has been shown in a number of cities worldwide. In

order to treat stormwater, improve biodiversity, and create recreational areas, Singapore has incorporated large-scale artificial wetlands and green corridors into its urban planning framework. By integrating bioswales, rain gardens, and green roofs into residential and commercial spaces, the city's "ABC Waters Program" transforms water infrastructure into multipurpose landscapes (Kumar *et al.*, 2025).

Another excellent example is Copenhagen, where the city's climate adaptation strategy heavily relies on natural solutions. Retention parks, permeable pavements, and green roofs have all been widely used to control heavy rainfall events, lowering the risk of flooding while establishing livable public areas. In a similar vein, Melbourne has implemented extensive green infrastructure, such as urban wetlands and water-sensitive urban design elements, to encourage stormwater collection and enhance drought resistance (Kumar *et al.*, 2025). These cities serve as examples of how green technologies improve live ability, environmental quality, and climate resilience in addition to addressing technical water challenges.

5. Digital Technologies in Urban Water Management

5.1 Internet of Things (IoT) and sensor networks for real-time monitoring- Sensor networks and the Internet of Things (IoT) have emerged as key elements of the digital transformation of urban water management, allowing for adaptive control of water systems in smart cities, data-driven decision-making, and real-time monitoring. Periodic data collection, delayed responses, and disjointed information systems are common limitations of traditional urban water management techniques (Expósito & Díez Cebollero, 2025). On the other hand, IoT-based monitoring frameworks greatly improve operational efficiency and sustainability by continuously providing high-resolution data across water supply, distribution, wastewater, and stormwater systems. In order to measure hydraulic, environmental, and water quality parameters in real time, IoT-based urban water monitoring systems rely on networks of interconnected sensors placed throughout water infrastructure. Flow rate, pressure, water level, temperature, pH, turbidity, electrical conductivity, dissolved oxygen, and residual chlorine are among the variables that are frequently observed (Alzahrani *et al.*, 2025).

Wireless communication technologies like LoRaWAN, NB-IoT, ZigBee, and cellular networks are often integrated with these sensors to enable dependable data transmission over vast urban areas with low energy consumption. Water utilities can identify system anomalies, evaluate infrastructure performance, and react quickly to new threats thanks to the availability of continuous data. IoT-based sensor networks have been shown in numerous studies to be successful in lowering non-revenue water and enhancing system reliability (Essamlali *et al.*, 2024). For instance, it has been demonstrated that real-time pressure and flow monitoring in urban distribution networks greatly improves leak detection capabilities, enabling utilities to spot unusual patterns suggestive of hidden leakages or pipe bursts. Case studies from smart cities in Europe and Asia show significant drops in water losses following the installation of IoT-enabled monitoring systems, underscoring their contribution to the preservation of limited water resources and enhancing economic efficiency.

IoT sensor networks are essential for maintaining urban water quality and safeguarding public health in addition to quantity monitoring (Figure 4). Continuous monitoring of water quality parameters enables early detection of contamination events caused by pipe corrosion, cross-connections, treatment failures, or external intrusions (Bawankar *et al.*, 2024). IoT-based water quality monitoring systems outperform traditional sampling-based methods by offering nearly real-time alerts and spatially detailed information, according to several studies. In densely populated cities, where delayed contamination detection can have serious public health repercussions, this capability is especially crucial (Hasan *et al.*, 2024).

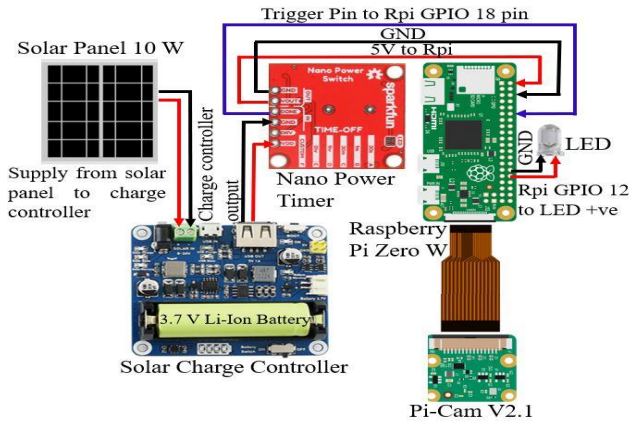


Figure 4. IoT-enabled Water Monitoring in Smart Cities with Retrofit and Solar-based Energy Harvesting (Bawankar *et al.*, 2024).

In order to support integrated urban water management, IoT technologies are also being used more frequently for stormwater and wastewater monitoring. In order to support early warning systems for urban flooding and sewer overflows, sensors installed in drainage systems and sewer networks monitor water levels, flow velocities, and overflow conditions. IoT-enabled monitoring enhances flood prediction accuracy and facilitates dynamic control of pumps, gates, and retention basins, according to research done in flood-prone cities. As urban areas experience more frequent and intense rainfall events due to climate change, these systems are becoming more and more crucial. Real-time IoT monitoring promotes more economical use of energy and water resources from a sustainability standpoint (Alzahrani *et al.*, 2023). IoT solutions help decrease unnecessary pumping, treatment, and emergency repairs, thereby reducing energy use and GHG emissions related to water services provided by smart cities. It has been observed that the efficiency and sustainability goals of smart cities can be enhanced by data-based solutions offered by IoT (Poyyamozhi *et al.*, 2024). Notwithstanding these advantages, some challenges inherent to water monitoring systems enabled by the IoT paradigm have also emerged from the literature. These involve durability related to fouling or degradation of the sensing technology itself, reliability of data due to potential sensor drift or environmental factors, interoperability of different sensor technologies to create a single platform, as well as certain threats such as security risks. Current research efforts are being directed toward improving the development of durable low-cost technologies, secure transmission systems, and common platforms (Miller *et al.*, 2023).

5.2 Big data analytics and machine learning for predictive management.

Big data analytics and machine learning have evolved as a paradigm-shifting digital technology in the area of predictive management in urban water resources, especially within the framework of smart cities (Figure 5). The current urban water network has the potential to create a massive amount of diverse data sources such as smart water meters, IoT sensors, SCADA systems, weather stations, satellite data, and socio-economic data sources (Expósito & Díez Cebollero, 2025).

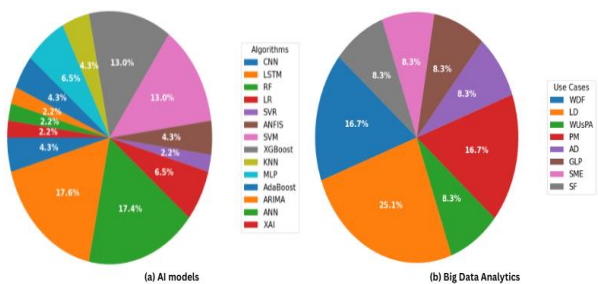


Figure 5. AI models and BDA used in water management (Amanatidis *et al.*, 2026).

The conventional data processing paradigm has become insufficient in the area of data volume, data velocity, and data complexity in the current dataset. Big data analytics offer a framework for the integration and processing of large datasets in relation to water, whereas machine learning enables smart decision-making through predictive models, thereby changing the paradigm of urban water resources management from a reaction-oriented approach to a proactive process (Amanatidis *et al.*, 2026). It is pertinent to state that the literature emphasizes that big data technology allows utilities to analyze, both in real-time and near real-time, their water infrastructure functionality by merging both structured and unstructured data from diverse sources. Furthermore, sophisticated analysis methods make it feasible for utilities to detect anomalies, trends, and patterns from their data. Specifically, for instance, research studies conducted in smart urban water utilities revealed that merging smart meter data with climatic data and demographics enables utilities to detect consumption trends that vary based upon seasonal, urbanization, and socio-economic dynamics.

Machine learning algorithms are essential to the use of predictive water management for their ability to identify non-linear patterns within data (Gaffoor *et al.*, 2020). Supervised models include Artificial Neural Networks, Support Vector Machines, and Random Forest models that are essential for predicting water demand, reservoir inflows, and water treatment plant behavior. Research has shown that machine learning approaches for demand forecasting are able to perform better than traditional statistical analysis by appropriately factoring in several influential elements like variations in the weather, the increase in population, land use patterns, and customer behavior (Ahmed *et al.*, 2024). Demand forecasting helps utilities optimize water resource allocation, cut operational expenses, and improve the dependability of the water supply.

Predictive maintenance is another major use of big data analytics and ML in the water sector. Predictive models, using the past sensor readings from water infrastructure, such as pressure, flow, vibration, and properties of the materials used in the pipes, are able to accurately establish which infrastructure is about to fail (Figure 6). There is scientific proof that the use of predictive maintenance models has ensured considerable reduction in the number of pipe bursts, thereby ensuring the economic viability of the water service in such cities (Dhulavvagol *et al.*, 2018).

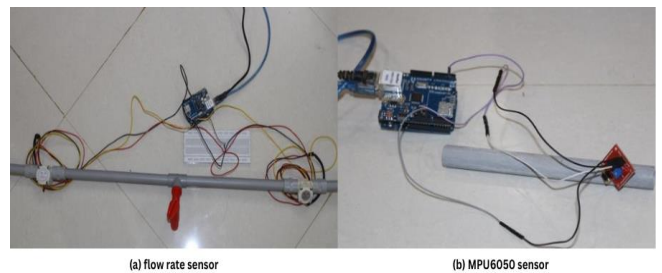


Figure 6. Pipeline setup for leak detection using flow rate sensor and MPU6050 sensor (Dhulavvagol *et al.*, 2018)

Big data analytics can further aid in the incorporation of climate and hydrological information into water management decision-making. Machine learning algorithms trained on past information of rain, temperature, and runoff have been widely employed in predicting drought, flood risk, and the effects of extreme weather on water infrastructure. Research in climate-exposed cities has shown the impact of predictive analytics on water management by improving the ability to respond and adapt to the problem by issuing warnings and undertaking scenario simulation and planning. The impact of climate change and its associated uncertainties and changes can create a challenge in conventional water management practices (Gaffoor *et al.*, 2020).

Despite this potential, there exist some limitations and difficulties that need to be considered while applying big data analytics and

machine learning in the context of water management in urban areas, as identified by the literature. There could be data quality problems related to missing and flawed data readings, as well as data that follows different formats. Moreover, there exists interpretability difficulty with complex machine learning algorithms that raise concerns for water managers and policy makers when the outcomes have broad social and economic impacts (Ogunkan & Ogunkan, 2025).

5.3 Artificial intelligence in leakage detection and demand forecasting.

Artificial intelligence has been identified as among the most influential digital technologies that can be applied when it comes to dealing with the challenges faced in water leakage detection and water demand forecast. In a conventional water distribution network, the process involved in the detection of leaks as well as the water demand forecast can be done through physical inspections or simply averages, which are some of the less precise methods when it comes to the behavior of the systems (Bagheri *et al.*, 2026).

In the area of leak detection, there has been an increasing trend toward the use of artificial intelligence methods in leak detection and localization in water distribution networks. AI algorithms based on data provided by pressure sensors, flow meters, acoustic sensors, and smart meters have been able to accurately detect anomalies in data that point toward the location of leaks or pipe bursts. Studies carried out by research scholars in both developed and developing countries show that AI-based leak detection models outperform existing traditional decision models based on thresholds and rules by a considerable margin, especially when dealing with old water distribution networks (Mashhadi *et al.*, 2021). There have also been reports that the use of AI technology in leak detection systems has contributed to early leak detection, thereby reducing water losses and minimizing effects on other networks in the vicinity. For instance, models that utilize past pressure and flow patterns have managed to pick small leaks that cannot easily be detected during physical site audits. The impact has been reported to have contributed to the reduction in non-revenue water in smart cities where AI technology has been implemented in the water management system (Vanijirattikhon *et al.*, 2022).

Artificial intelligence is also important in urban water demand forecasting. Water demand forecasting is important to help manage the supply and demand of water in any urban area. AI water demand forecasting models use various factors such as past water demand data, weather data, growth data, land use data, and socio-economic data. AI models can process data in a way that can model past data patterns much more effectively than any other model. Studies have consistently shown that artificial intelligence models can forecast water demand more effectively than any other model (Alhendi *et al.*, 2022). The ability for water companies to optimize their pumping and treatment schedules through the use of artificial intelligence is possible if the company is able to predict their demands through artificial intelligence. The application of AI is important in predicting water demands during times when the water demand is beyond the usual trends, such as during heat waves and droughts. Through AI, water companies are able to adopt a water demand management strategy that makes their water systems resilient (Bagheri *et al.*, 2026).

Despite these advantages, the deployment of Artificial Intelligence in leakage detection and demand forecasting has some challenges, as mentioned in the literature. Data issues of the type of availability, quality, and consistency are major constraints, especially for cities that lack surveillance infrastructure. The difficulty of interpretation of complex AI models also falls under the limitations of deployment (Taloma *et al.*, 2025).

Current trends, especially in the most recent literature, are shifting towards the development of Explainable AI solutions by combining data science with the knowledge of the physical system itself for better visualization and acceptability.

5.4 Cloud computing and GIS applications in water distribution and quality control.

Cloud computing and geographic information system (GIS) technology are some of the key digital technologies in the

management of water in a city. Cloud computing is emerging as a cost-effective and reliable option for the storage and processing of data created by the use of water sensors and water meters in a city. GIS technology is a digital technology in the management of water in a city. It offers a critical function in the management of the water distribution network in a city and ensuring water quality in a smart city (Habeeb & Weli, 2021). Cloud computing solutions make real-time as well as historical data from across the water infrastructure in a municipality centrally available. Cloud computing solutions for supervisory/decision support systems support the integration of various types of data from differing sources such as IoT devices, hydraulic models, and customer information systems into a single platform (Alshattnawi, 2017).

Research studies show that cloud-based water management systems enhance operational efficiency through the monitoring and identification processes that occur on a real-time basis and facilitate collective actions among various operational units. Additionally, cloud platforms make it easier to implement analytics and artificial intelligence algorithms that do not require heavy computations on site.

The use of GIS applications is very important in the spatial management of water networks because it enables the mapping and analysis of water pipes, valves, water reservoirs, water pumps, and water services. The use of GIS technology helps in the management of water infrastructure because it enables the optimization of networks, zoning, and the planning of water infrastructure development. Several studies have shown the importance of the integration of GIS and real-time water utility information because it helps in the creation of water utility awareness and the identification of areas of water risk leakages and interruptions (Patel & Nihalani, 2023). The use of GIS technology is of great importance in densely populated cities and urban areas.

Cloud computing technology is also common in the field of GIS, as it is utilized in water quality management in urban areas. Cloud data platforms make it possible to process large amounts of data collected from water quality sensors at water treatment plants, as well as water distribution points. The technology allows the water quality parameters to be analyzed instantly while also triggering alerts if the water quality goes above the permissible limit. There is research suggesting that water quality management through the use of cloud technology can provide faster reaction times to water quality incidents as well as ensure greater adherence to water quality regulation standards (Nethanani *et al.*, 2025). GIS improves water quality management by facilitating spatial analysis for contaminated sources, vulnerable areas, and exposed populations. It has been shown that water quality mapping using GIS can aid in the recognition of water sources and areas that can be vulnerable to contamination because of old infrastructure, industries, and land use. Spatial analysis techniques are also harnessed to simulate the migration of contamination in water distribution systems and the probable effects that may arise from contamination events in various districts. Cloud computing and GIS integration also contribute to collaboration and transparency within water management in urban areas (Arumugam *et al.*, 2025).

Cloud computing allows various parties, including water resources and data, thereby promoting collaborative decision-making. Research works also stress the importance of using Web-enabled GIS maps, cloud-based visualization, or both in improving public communication and accountability in water service delivery (Merlo *et al.*, 2025).

6. Digital Twins and Smart Water Systems

6.1 Concept of digital twins in urban hydrology.- A digital twin is a continuously updated virtual, dynamic, and digital replica of physical urban water systems, integrating real-time data, mathematical models, and computational simulations. In urban hydrology, digital twins are utilized to simulate the actual behaviour of water distribution networks, drainage systems, rivers, reservoirs, and wastewater infrastructure. Unlike traditional static models, digital twins evolve in real time, based on continuous data ingestion from IoT sensors, smart meters, weather forecasts, and operational databases (Movva, 2024) (Figure 7).

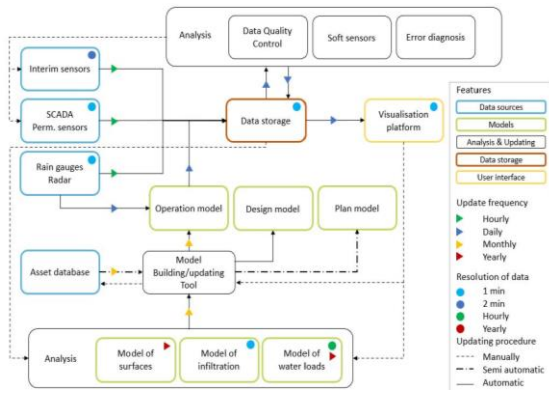


Figure 7. Digital Twin for the Urban Drainage System (Movva, 2024).

Literature underlines that digital twins in urban hydrology enable holistic views of complex interactions between natural hydrological processes and engineered water infrastructure. They enable the integrated modeling of rainfall-runoff processes, surface water-groundwater interactions, and dynamics of urban drainage under different climatic and urbanization scenarios (Kim & Bartos, 2024). This virtual environment provides city authorities with an opportunity to test management strategies and system vulnerabilities, and enables them to explore future scenarios without disrupting physical operations. This capability is increasingly recognized as crucial for managing water resources in rapidly growing and climate-stressed urban environments.

6.2 Real-time simulation and decision support systems.- Among the most important benefits that can be obtained through the use of digital twins in smart water systems is the possibility of simulating the system in a real-time manner. This is possible since the digital twins are capable of continuously simulating the behavior of the water systems using data from real-time sensors along with models based on the hydraulic, hydrologic, and water qualities (Ghorbani Bam *et al.*, 2025). Studies have found that the use of real-time simulations on digital twins improves the supportive function of decision support systems in managing flooding, water supply, and wastewater. For instance, in the case of heavy rainfall, the simulation of runoff, sewer capacity, or flooding in a real-time digital twin can aid in taking advance action on gate control, pumping, and storage in retention basins. Likewise, in water supply systems, the simulation in a digital twin can aid in optimizing water supply in a smart city by optimizing pumping plans, storage, or water pressure in a smart, energy-efficient, and efficient, reliable, or less-disrupted manner (Zhao *et al.*, 2025).

6.3 Integration of digital twins with water infrastructure for predictive maintenance.

The use of digital twins in conjunction with physical water infrastructure has remarkably enhanced the efficiency of predictive maintenance in water management. The continuous analysis of information derived from sensors linked to water infrastructure, including information on water pressure, water flow, vibrations, temperature, and condition, allows digital twin technology to predict deterioration and failure of water infrastructure (Ghorbani Bam *et al.*, 2025). Research reveals the application of digital twins improves asset management by predicting the remaining useful life of pipes, pumps, and valves, and by optimizing the scheduling of maintenance activities according to risk and criticality. In the context of old water infrastructures in urban settings, this proves very useful, as unforeseen breakdowns, water losses, and maintenance expenses can be minimized. Research reveals the application of predictive maintenance in combination with digital twins can raise the resilience and longevity of infrastructure, thereby promoting economic and environmental sustainability (Ghorbani Bam *et al.*, 2025). The combination of digital twins and AI improves the accuracy of defect or fault detection and enables automatic generation of maintenance suggestions.

7. Integration of Digital and Green Technologies

7.1 Synergy between digital monitoring and green infrastructure.- The fusion of digital monitoring technology with green infrastructure is one of the most important breakthroughs in sustainable urban water management. Green infrastructure technologies such as green roofs, permeable pavement, bioswales, constructed wetlands, or urban rain gardens have gained prominence as effective stormwater management systems to promote water recharge as well as to ameliorate urban microclimates. However, their efficiency is largely affected by local climatic factors, soil type, vegetation health, or maintenance regimes. Digital technologies such as IoT technology or remote sensing can make green infrastructure more efficient through continuous monitoring systems (Chen *et al.*, 2023).

Studies have indicated that the use of sensor monitoring of soil moisture, rates of infiltration, water level, and vegetation status provides urban managers with a way to evaluate real-time functionality of green infrastructure systems. For instance, the use of IoT-based bioswales that employ moisture sensors and flow sensors provides a real-time method to manage water retention and outflow rates, enhancing the effectiveness of stormwater management. Digital technologies and monitoring systems provide an early warning system that alerts managers of the system malfunction due to any blockage issues, vegetation stress, or any form of infrastructural deficit (Scarborough *et al.*, 2023).

7.2 Hybrid systems for stormwater reuse, irrigation, and flood mitigation.

The hybrid water management system that employs green and digital infrastructure is now identified as an efficacious strategy for complementary use of water from storms, irrigations in urban areas, and also control and mitigation strategies for floods. Green roofs and rainwater harvesting systems with smart valves and sensors also have the capacity to harvest water during rainfall and then allow the water to seep out when there is a requirement for irrigation and non-potable purposes (Sapkota *et al.*, 2023).

Studies have shown the importance of smart hybrid systems, which greatly improve the resilience of cities against flooding created in urban areas. The use of smart technology to control retention basins and wetlands improves their efficiency and reduces the flood risks of cities. The implementation of smart technology in water systems ensures water conservation through the use of alternative water sources of water for landscaping and farming. Water preservation and reduction of the flood risk of cities, therefore, will greatly benefit from the implementation of smart technology (Aziz *et al.*, 2024).

7.3 Multi-scale integration: building → neighborhood → city level.- The effective integration of digital and green technologies demands a multiscale approach that connects the individual building, neighborhood, and citywide into coherent water management systems. At the building scale, smart rainwater harvesting systems, green roofs, and gray water recycling units are fitted with sensors and control devices to enable localized water reuse and runoff reduction. Such solutions minimize the burden on centralized infrastructures while improving water self-sufficiency (Walter, 2024).

At the neighborhood scale, interconnected green spaces, permeable surfaces, and decentralized treatment systems can be digitally coordinated to collectively manage stormwater. Research demonstrates that neighborhood-scale integration tends to enhance overall system performance by distributing water storage and treatment functions among multiple sites. At the city scale, digital platforms and GIS-based systems integrate data from buildings and neighborhoods to support strategic planning, real-time coordination, and emergency response. Multi-scale integration enhances system resilience, flexibility, and scalability, enabling cities to respond effectively to urban growth and climate variability (Kong *et al.*, 2017).

7.4 Tools for planning (e.g., SWMM, CityWat, MIKE Urban).- Advanced models and decision support systems are severely important in the integration process between digital and green technologies in the field of sustainable water resource management.

Examples of models employed in stormwater management, urban flooding, or water resource management in urban areas are the Storm Water Management Model (SWMM) computer program, the CityWat model, or the MIKE Urban model. These models enable scenario analyses or the evaluation of designs and policies concerning the combined use of digital and green technologies (Nagal & Prabhakar, 2025). Studies have shown that the use of SWMM is most successful for simulating runoff and assessing the effectiveness of green infrastructure practices such as porous pavements and detention ponds. CityWat allows for an integrated water plan for the water supply, wastewater, and storm water systems at various scales. MIKE Urban allows for sophisticated simulation for water flow and water quality and can be used for various control and digital twin applications. The use of the above models and data from online monitoring improves the accuracy and adaptability of the models (Qin *et al.*, 2025).

7.5 Framework for integrated sustainable water management.

The development of a broader framework that integrates sustainable water management would play a crucial role in realizing the full potential that comes from merging digital and green technologies. These frameworks exhibit a focus on system integration, data-driven decision-making, engagement among stakeholders, and sustainability. The proposed frameworks from research in literature include aligning technological innovation and sustainability in terms of environmental sustainability, equity, and economic viability (Bosco *et al.*, 2025). A normally integrated framework might have important elements like real-time observation, use of predictive models, deployment of green infrastructure, and governance solutions for adaptation. The digital platform helps in the evaluation of performance, while green infrastructure can utilize ecosystem services like flood management, clean water, and climate regulation for cities in a beneficial manner. Research reveals that a proficient framework should recognize the importance of policy support, development of institutional capacities, and engagement with societies to adapt to long-term acceptance and implementation (Zarei & Shahab, 2025).

7.6 Challenges and Limitations

Table 1 presents the major challenges and limitations associated with sustainable water systems, highlighting technical, economic, environmental, and institutional constraints.

Table 1. Specific challenges and limitations related to sustainable water management

Category	Specific Challenges	Explanation	References
Technical	Data interoperability	Various sensors, Internet of Things devices, and monitoring platforms from various vendors are frequently integrated into urban water systems. The inability to exchange data seamlessly due to a lack of standardized protocols and formats lowers system efficiency and predictive capability.	(Zyoud, 2025)
	Infrastructure cost	Many cities, particularly those in developing nations, may find it difficult to afford the substantial upfront costs associated with installing and maintaining sensors, communication networks, cloud platforms, and GIS systems.	(Tan & Taeihagh, 2020)
	Maintenance	In challenging conditions, sensors and smart infrastructure are vulnerable to fouling, calibration drift, or failure. To guarantee accuracy and dependability, regular maintenance and updates	(Tan & Taeihagh, 2020), (Costa <i>et al.</i> , 2024)

		are crucial.	
Institutional	Governance and policy gaps	The coordinated application of digital and green water solutions may be hampered by disjointed institutional structures and ambiguous roles. Innovative technologies like digital twins and smart metering might not yet be supported by policies.	(Tan & Taeihagh, 2020), (Bibri & Huang, 2025)
	Lack of skilled personnel	Trained personnel in data analytics, hydraulic modelling, artificial intelligence, and Internet of Things maintenance are necessary for advanced digital and integrated water management systems. There is a lack of expertise in these fields in many cities.	(Tan & Taeihagh, 2020), (Nagal & Prabhakar, 2025)
Environmental and Social	Public acceptance	Adoption of smart water systems and green infrastructure may encounter resistance because of perceived inconvenience or unfamiliarity. Participation in the community is essential to acceptance.	(Alli <i>et al.</i> , 2025), (Qi & Barclay, 2021)
	Privacy and data security	IoT and cloud-based systems gather location and consumption data in great detail, which raises privacy issues and possible cybersecurity threats.	(Ammar Deh, 2024)
	Resilience to climate extremes	The dependability of digital and green systems may be put to the test by extreme weather events, necessitating the use of redundancy and adaptive techniques to preserve functionality.	(Leandro Bertholdo <i>et al.</i> , 2025)
Economic	Cost-benefit considerations	Short-term financial analyses may not always justify a large initial investment, even though integrated systems can provide long-term savings.	(Focacci, 2025)
	Lifecycle implications	To assess the sustainability and financial viability of smart water interventions, full lifecycle costs including installation, operation, maintenance, and decommissioning must be considered.	(Dai <i>et al.</i> , 2025), (Safarpour <i>et al.</i> , 2022)

8. Future Directions and Research Opportunities

The vision of sustainable urban water management can be realized by the harmonious application of digital innovations, renewable energy, and natural solutions to build circular and resilient water systems. Emerging technologies such as Artificial Intelligence, Blockchain, and Digital Twins will have a revolutionary application to make urban water management predictive, transparent, and adaptive through secure digital platforms. Artificial Intelligence will optimize water distribution networks and enable water demand forecasting as well as leak detection. Blockchain will enable secure water transaction platforms. Digital Twins will provide real-time simulation tools to make water management operational as well as strategic (Dai *et al.*, 2025). Besides digital innovations, solar-powered water pumps, water-to-energy converters to convert wastewater to energy, as well as water reuse systems through renewable energy platforms will make water management more

efficient and sustainable by reducing water-embedded greenhouse gas emissions as well as water-energy nexus water management sustainable. Future research must emphasize the application of transdisciplinary models to address biological as well as digital connectivity as well as hyper-connectivity through ecology-structured water modeling platforms to address natural as well as digital water connectivity (Alireza Zakariazadeh *et al.*, 2024).

However, along with the advent and the successful implementation of these technologies, there is a need for a robust regulatory and investment environment. Based on the understanding and consideration of all the above-mentioned dimensions – technological, ecological, and others – the future research can lead the way to a more resilient and efficient water management system in the city (Dai *et al.*, 2025).

Conclusion

This particular review offers insights into the revolutionary applications of the integration of digital technology solutions with green infrastructure for the effective management of water in urban settings. Principal observations pointed towards the fact that the use of IoT monitoring, big data analysis, AI, digital twin technology, and cloud/GIS platforms results in the better application of decision-making techniques in relation to the management of water in urban settings, whereas the application of nature-based solutions such as green infrastructure, bioswales, and constructed wetlands results in the effective management of stormwater runoff in urban regions. The need for the future of water management in urban areas entails the fact that a comprehensive vision for water sustainability must involve the application of advanced technology solutions, decentralized renewable energy systems, and transdisciplinary modeling tools for the effective development of water products for the future.

Conflict of Interest

Authors declare that there is no conflict of interest in any form that could have influenced the research work reported in this paper.

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