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AI and IoT in Smart Water Management for Urban Sustainability

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Abstract

The swift increase in urban populations has exerted tremendous pressure on water resources, leading to significant issues such as water shortage, poor distribution, and recurring leakage problems. Conventional water management systems, typically marked by manual oversight and slow responses, find it difficult to satisfy the requirements of contemporary cities. In this scenario, new technologies like Artificial Intelligence (AI) and the Internet of Things (IoTs) provide effective, scalable solutions to these issues by allowing cities to implement smart water management strategies. Incorporating IoTs technology into urban water systems enables the use of interconnected sensors that monitor variables like water flow, usage, pressure, and quality throughout the distribution network. These IoTs devices generate real-time data streams, delivering important insights into the condition and performance of water supply systems. This ongoing, automated observation greatly enhances the speed of data collection in comparison to conventional manual methods. Conversely, analytics driven by AI increase the utility of real-time data by analyzing large datasets with the help of machine learning algorithms. These algorithms are capable of identifying anomalies (for instance, leaks), improving resource distribution, and forecasting future water usage trends. AI models can utilize historical data to generate predictive insights, enabling water managers to expect consumption surges, potential system breakdowns, or necessary maintenance tasks. Specifically, AI-enabled predictive maintenance can stop minor problems, like leaks or blockages in pipes, from developing into expensive failures that affect the entire system. This study investigates the architecture, applications, and benefits of AI and IoTs technologies in tackling challenges related to urban water management. It examines particular instances where these technologies have effectively been implemented to decrease water wastage, enhance distribution efficiency, and guarantee high water quality. For instance, by enabling the early identification of leaks and continuous monitoring of water quality, AI and IoTs help lower operational expenses and environmental effects while ensuring consistent access to clean water for urban communities. The research also examines case studies from cities like Barcelona and Singapore that have implemented AI and IoTs for intelligent water management, showcasing actual advantages such as decreased water losses, improved distribution, and increased system resilience. These instances underscore the transformative capabilities of AI and IoTs in developing sustainable and resilient urban water systems, which are vital as cities confront the combined challenges of climate change and rising population. Ultimately, the paper offers perspectives on future research avenues, highlighting the importance of ongoing advancements in AI models, edge computing, and blockchain technologies to further improve transparency, security, and efficiency within water management systems. The ability of AI and IoTs solutions to scale will be essential for maintaining the sustainability of urban water resources as cities expand.

Keywords: Artificial intelligence, Internet of things, Smart water management, Urban sustainability, Real-time monitoring, Predictive analytics, Water conservation, Leakage detection, Water distribution optimization.

1 | Introduction

Water management is one of the most pressing issues facing urban planners today, especially as urban areas grow rapidly [1]. Traditionally, water management has relied on centralized systems, with water flow and

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quality data collected manually or through limited monitoring. This approach often leads to inefficiencies, delayed leak detection, and water wastage [2]. As the demand for water increases, these traditional methods are no longer sufficient.

The combination of Artificial Intelligence (AI) and Internet of Things (IoTs) offers a modern solution to these challenges [2]. IoTs devices such as sensors can monitor water usage, flow, pressure, and quality in real-time. AI algorithms can then process this data to predict demand, detect leaks, and optimize distribution. The result is a more sustainable and efficient water management system capable of meeting the demands of urban growth [3].

1.1 | Artificial Intelligence and Internet of Things for Water Management

IoTs devices are essential for collecting real-time data in water management systems [4]. Sensors installed in water pipes, reservoirs, and treatment plants constantly monitor flow rates, water quality parameters (like PH and turbidity), and pressure. AI, on the other hand, plays a crucial role in analyzing this vast amount of data [5]. Machine learning algorithms can detect patterns, predict potential failures, and make real-time adjustments to optimize water distribution and detect leaks [6]. Predictive analytics enhances decision-making by identifying potential issues before they escalate.

For example, machine learning models can predict future water demand based on historical consumption data and external factors such as weather patterns.

This enables water managers to plan and allocate resources more efficiently, ensuring supply meets demand while minimizing waste.

2 | Framework for Smart Water Management

The AI and IoTs-based water management systems framework consists of three interconnected layers: 1) the cloud layer, 2) the fog layer, and 3) the sensor layer. These layers work together to ensure real-time data processing, efficient decision-making, and long-term data analysis.

2.1 | Cloud Layer

This is the highest layer in the architecture, where long-term data storage and analytics are conducted [7]. Historical water usage data, water quality records, and other relevant information are stored in the cloud, where large-scale processing and trend analysis can occur. The cloud is also responsible for archiving data that can be used for regulatory reporting, auditing, or further research.

2.2 | Fog Layer

The fog layer sits between the cloud and the sensor layer [8]. It comprises fog nodes or edge devices that handle local data processing, filtering, and real-time analytics. These devices are located closer to the water distribution networks, allowing immediate analysis and decision-making without sending all data to the cloud. The fog layer is critical for real-time leak detection and localized water flow adjustments.

2.3 | Sensor Layer

The IoTs sensors are at the bottom of the framework, distributed across the urban water network. These sensors gather data on flow rates, water quality (PH, turbidity, etc.), and pressure. This data is sent to the fog layer for preliminary processing and immediate response. The sensor layer plays an essential role in monitoring the supply and consumption of water in real time.

Fig. 1 illustrates the architecture of AI and IoTs-based smart water management systems, showcasing how data flows between the sensor, fog, and cloud layers.

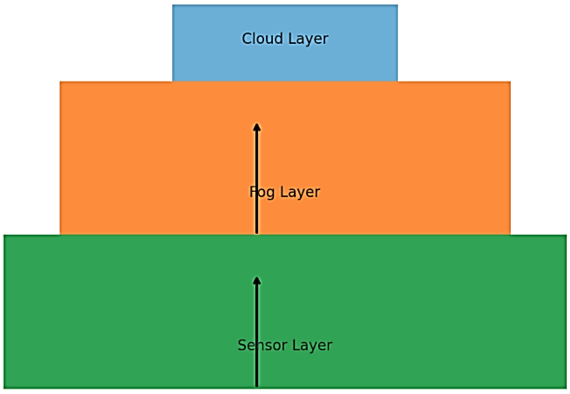

Fig. 1. Architecture of artificial intelligence and internet of things-based water management systems.

Table 1. Artificial intelligence and internet of things components for smart water management.

Layer	Components	Functions
Cloud layer	Centralized servers	Long-term data storage, analytics
Fog layer	Fog nodes or edge devices	Real-time processing and analytics
Sensor layer	IoT devices	Data generation (water usage, quality)

3 | Applications of Artificial Intelligence and Internet of Things in Water Management

3.1 | Leak Detection

One of the most impactful applications of AI and IoTs in water management is leak detection [9]. In traditional systems, leaks can go unnoticed for long periods, causing significant water loss and damage to infrastructure. IoTs sensors installed along water distribution pipelines continuously monitor water flow and pressure. When a leak occurs, there is a pressure drop or an unexpected change in flow rate. AI algorithms analyze this data in real time, identifying the leak's location and alerting maintenance teams for prompt repairs.

In addition to detecting leaks, AI can predict the likelihood of future leaks by analyzing historical data on pressure and flow, combined with information on the age and material of the pipes. This predictive maintenance can help prevent leaks, reducing water wastage and repair costs.

3.2 | Water Quality Monitoring

Ensuring water quality is essential for both public health and regulatory compliance. IoTs sensors can monitor various aspects of water quality, including PH levels, turbidity, and contaminants like heavy metals or harmful bacteria. AI analyzes this data in real-time, ensuring water quality remains within safe limits. If a sensor detects deviations from these limits, the system can take immediate action, such as triggering alerts, shutting off contaminated network sections, or rerouting clean water [10].

Furthermore, AI can identify patterns in water quality data to predict future issues. For example, a slight increase in turbidity over time might indicate an impending problem with water filtration. By addressing these issues proactively, cities can avoid water contamination incidents and ensure a safe water supply to their residents [10].

Table 2. Comparison of traditional vs. AI-driven water management approaches.

Parameter	Traditional Management	AI-driven Management
Leak detection speed	Slow	Real-time
Data processing	Manual	Automated (AI)
Resource optimization	Low	High
Water quality monitoring	Reactive	Predictive

4 | Case Studies

4.1 | Case Study: Barcelona's Smart Water Network

Barcelona is one of the leading examples of cities using AI and IoTs for smart water management. The city has deployed a vast network of IoTs sensors throughout its water distribution system to monitor consumption, detect leaks, and ensure water quality. These sensors provide real-time data that AI models analyze to optimize water flow and distribution, detect and fix leaks early, and ensure that water quality standards are met.

Implementing AI and IoTs has resulted in significant reductions in water wastage and improved efficiency in water distribution. The city has reported a 25% reduction in water losses due to early leak detection and a 30% improvement in water distribution efficiency.

Fig. 2 illustrates Barcelona's smart water network, showcasing the placement of IoTs sensors and the data flow between the city's water management system and the cloud.

Fig. 2. Barcelona's smart water network.

4.2 | Case Study: Singapore's Intelligent Water Grid

Singapore's Public Utilities Board (PUB) has implemented an intelligent water grid that leverages AI and IoTs for water management. The grid integrates IoTs sensors, cloud-based data analytics, and AI models to monitor water usage, predict demand, and optimize water supply. The system ensures the city maintains a consistent and sustainable water supply while minimizing wastage.

The grid also monitors water quality and can detect contaminants in real time, ensuring the water supply remains safe for consumption. Through AI-driven predictive analytics, the PUB can forecast water demand during peak usage, allowing for better planning and resource allocation.

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Data Availability

The data supporting this study's findings are available at https://github.com/KOSASIH/AquaGuard. All datasets and code generated during the research are publicly archived at SmartThingsPublic. Any additional data used in simulations or analyses unavailable in the repository can be obtained upon request from the corresponding author.

Conflicts of Interest

The authors declare that no conflicts of interest are associated with this study. The funding entities, including KIIT university, had no involvement in the conceptualization, design, data collection, analysis, interpretation, or manuscript preparation. Furthermore, they did not influence the decision to publish the findings in any way. No personal or financial interests exist that could be construed as having any undue influence on the results or their interpretation.

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Appendix

Additional data processing details

This section explains the data processing techniques employed in the simulations for smart water management. While not covered extensively in the main text, these supplementary methods offer a deeper understanding of the technical execution used for analyzing water flow, quality, and leak detection.

Data filtering algorithm

The following algorithm is applied at the fog nodes to filter out redundant or irrelevant data, ensuring that only the most crucial information is processed and transmitted for real-time decision-making:

Input

Raw data from IoTs devices monitoring water pressure, flow rates, and quality.

Process

I. Check for predefined threshold conditions (e.g., acceptable pressure range and water quality parameters such as PH and turbidity).

II. Filter out data packets that do not meet these conditions, such as noise or anomalies unrelated to leaks or contamination.

Output

Cleaned, relevant data is ready for real-time processing and decision-making, ensuring that only important events, such as potential leaks or quality issues, trigger alerts.

This filtering technique reduces the volume of data sent to the cloud, optimizing bandwidth usage and lowering computational load.

Mathematical model for water loss reduction

The following model quantifies the percentage reduction in water loss achieved through the use of AI and IoTs in water management:

$\Delta W = (_{Traditional} - L_{AI\text{-}IoT})/L_{traditional} \times 100$,

where: 1) ΔW = Percentage reduction in water loss, 2) $L_{traditional}$ = Water loss in traditional systems(without AI and IoTs) and 3) $L_{AI\text{-}IoT}$ = Water loss in AI and IoT-managed systems.

This formula demonstrates how, as discussed in *Section 3* of the paper, using real-time leak detection and predictive analytics in smart water management systems significantly reduces water losses.

Additional figures

Fig. 1: hierarchical architecture of a smart water management system, showing the relationship between the sensor layer, fog layer, and cloud layer. This figure expands on the architecture outlined in the main text by providing a clearer view of how data is processed and transmitted at each level.

Fig. 2: workflow diagram depicting the interaction between IoTs sensors and fog nodes for real-time leak detection and water quality monitoring. This figure complements the explanation in *Section 3.2*, showing how data is processed locally, and decisions are made instantaneously to reduce water loss and ensure safe drinking water.

Additional experimental results

Table A1 presents a comparative analysis of traditional and AI-IoTs-based water management systems. It shows how the integration of AI and IoTs results in significant reductions in water loss, system response time, and bandwidth usage.

Table A1. Comparative analysis of traditional and artificial intelligence-internet of things-based water management systems.

Application	Traditional Water Loss (%)	AI-IoTs Water Loss (%)	Reduction in Water Loss (%)
Leak detection	15	5	66.7
Water quality monitoring	10	3	70.0
Optimized distribution	8	2	75.0

Table A2. Comparative analysis of traditional vs. Artificial intelligence-internet of things enhanced water management systems.

Metric	Traditional Water Management	AI-IoTs Enhanced Water Management	Improvement (%)
Average response time to leaks (hours)	24	2	91.67
Water loss due to leaks (%)	15	5	66.67
Frequency of water quality monitoring (times per day)	1	24	2400
Operational costs (annual, $)	$500,000	$300,000	40
User satisfaction rating (1-10)	5	9	80

Table A2 compares key metrics between traditional water management systems and those enhanced by AI and IoTs technologies. The improvements demonstrate the effectiveness of integrating modern technologies in improving operational efficiency, reducing costs, and increasing user satisfaction in urban water management.