Smart Water Management :

Leveraging AI and IoT for Sustainable Solutions

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ABSTRACT

Water management has become a critical topic of discussion at numerous international forums. In response to the escalating global water crisis, water harvesting and recycling have emerged as essential strategies. Over 4 billion people experience severe water scarcity for at least one month a year[1]. To effectively address this challenge, greater focus is needed on implementing advanced water management techniques across various application areas. Given the increasing population density, there is an urgent need to adopt intelligent water management systems that ensure efficient distribution, conservation, and maintenance of water quality standards for diverse uses. India houses 18% of the world's population but has only 4% of the world's freshwater resources[2].

Around 2.2 billion people worldwide lack access to safely managed drinking water services[3]. This paper explores key areas vital for effective water management, including recent advancements in wastewater recycling, water distribution, rainwater harvesting, and irrigation practices. These domains increasingly rely on Artificial Intelligence (AI) models, tailored to unique and variable data types. As such, there is a growing demand for versatile algorithms capable of addressing the challenges across these applications. Integrating AI and Deep Learning (DL) techniques with Internet of Things (IoT) frameworks can lead to the development of smart water management systems, promoting the sustainable use of natural water resources.

Keywords: Internet of things (IoT); deep learning (DL); artificial intelligence (AI); water distribution; water quality; waste water management; water conservation

1 UN World Water Development Report 2023
2 NITI Aayog – Composite Water Management Index (CWMI), 2019
3 UN-Water, 2023

Introduction

When we think of Artificial Intelligence (AI), what comes to mind? Robots? Human-like machines designed for widespread destruction and chaos? As AI's popularity has surged in recent years, we are not only becoming more comfortable with its use but are also actively seeking ways to harness it to our advantage. With AI technologies continuing to revolutionize various industries, the global AI market is projected to grow at an annual rate of 37.3% from 2023 to 2030[4].

Data-driven "intelligent" applications are increasingly transforming everyday life. Forward-thinking water utilities have the opportunity to capitalize on this digital revolution to boost their performance. By leveraging artificial intelligence algorithms and big data analytics, these utilities can make the most of available information to drive smarter decision-making, improve service delivery, and lower operational costs. By 2025, an estimated half of the world's population will be living in water-stressed areas[5] .

AI extends beyond traditional pattern recognition and data analytics. It presents a range of opportunities that could potentially revolutionize the water industry in ways we've never imagined. Climate change and population growth are escalating pressures on water resources and infrastructure globally. While millions are aware of water-related issues, the water cycle remains an enigma, even for those responsible for studying how water flows on, above, and beneath the earth's surface. 21 Indian cities, including Delhi, Bengaluru, and Hyderabad, are predicted to run out of replenishable groundwater by 2030[6] or even much early.

Governments and NGOs possess vast amounts of water-related data. By incorporating artificial intelligence (AI) into water management, this data can be leveraged to conserve water supplies, minimize contaminants, ensure more equitable distribution, enhance water quality, and provide better protection against floods and droughts. AI is transforming water management by optimizing resource use, recycling water, low generation of waste water and building more resilient water infrastructures and treatment processes.

How AI can contribute in the system

Artificial Intelligence (AI) is a branch of computer science focused on developing systems capable of performing tasks that typically require human intelligence. It involves designing algorithms that can process, analyse, and interpret vast amounts of data, enabling machines to simulate human cognitive functions such as learning, planning, decision-making, and problem-solving[7].

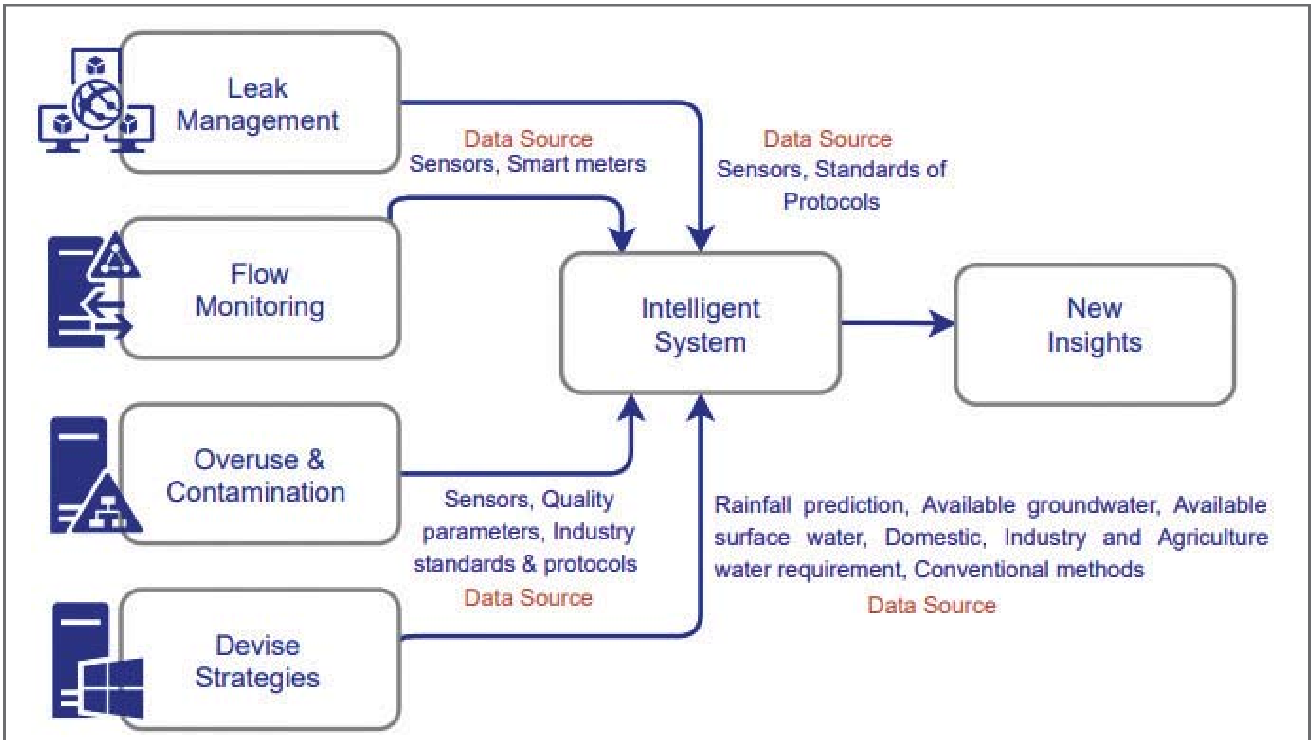
As climate change intensifies and resources—both financial and human—become increasingly constrained, the water sector is grappling with growing challenges. Unpredictable weather patterns, water scarcity, and pollution are placing immense pressure on existing infrastructure, treatment systems, and the professionals who operate them[8].

AI technology offers transformative potential for the future of water and wastewater management, helping to ensure the sector's resilience and long-term sustainability. Here are six critical ways AI is helping to solve problems across the water industry:

1. **Water Quality Monitoring:** AI can continuously monitor water quality in real time by analysing data from sensors deployed in rivers, lakes, and distribution systems. These AI algorithms detect shifts in parameters such as turbidity, pH, or chemical composition, flagging contaminants and public health threats like pollution plumes, harmful algal blooms, eutrophication, or disease-causing pathogens.
2. **Leak Detection and Prevention:** By evaluating data from flow meters and pressure sensors, AI can identify anomalies that suggest leaks in water distribution networks. Early detection allows utilities to act proactively, preventing water loss, minimizing service disruption, and lowering repair costs.
3. **Infrastructure Maintenance:** AI can process real-time data to monitor and optimize flow pressure, velocity, and energy consumption across water and wastewater systems. It also enables predictive maintenance by diagnosing infrastructure issues such as sewer blockages or equipment defects-often

4 Grand View Research, 2024
5 UN Environment Programme (UNEP)
6 NITI Aayog CWMI Report
7 Global Water Intelligence. 2019. Water's Digital Future. London. https://www.globalwaterintel.com/products-and-services/market-research-reports/watersdigital-future.
8 Sensus. 2020. Improving Utility Performance Through Analytics: Market Research Report. White Paper. https://sensus.com/resources/white-papers/improvingutility-performance-through-analytics-market-research-report/.

Figure 1: Harnessing intelligent systems for water management



Source: Sustainability 2022, 14, 13384. https://doi.org/10.3390/su142013384

before they escalate. Smart systems can adjust operations during extreme weather to prevent sewer overflows and send rapid alerts in case of sudden discharges, improving emergency response.

4. **Flood Prediction and Management:** Machine learning models can analyse real-time weather data, river levels, and past flood events to predict potential flooding. With accurate forecasts and timely alerts, local authorities and emergency services can prepare in advance, minimizing damage and safeguarding communities.
5. **Water Conservation:** AI can optimize water usage in agriculture and urban areas by integrating data on climate conditions, soil moisture, and crop requirements. These insights support efficient irrigation scheduling, reducing water waste and promoting sustainable water practices.
6. **Water Resource Management:** Through comprehensive data analysis of water availability, usage trends, and population dynamics, AI supports smarter decision-making in resource allocation and infrastructure development. This is especially valuable in regions facing water scarcity, enabling more strategic and equitable management of water supplies[9].

Role of Artificial Intelligence in Water Supply Management

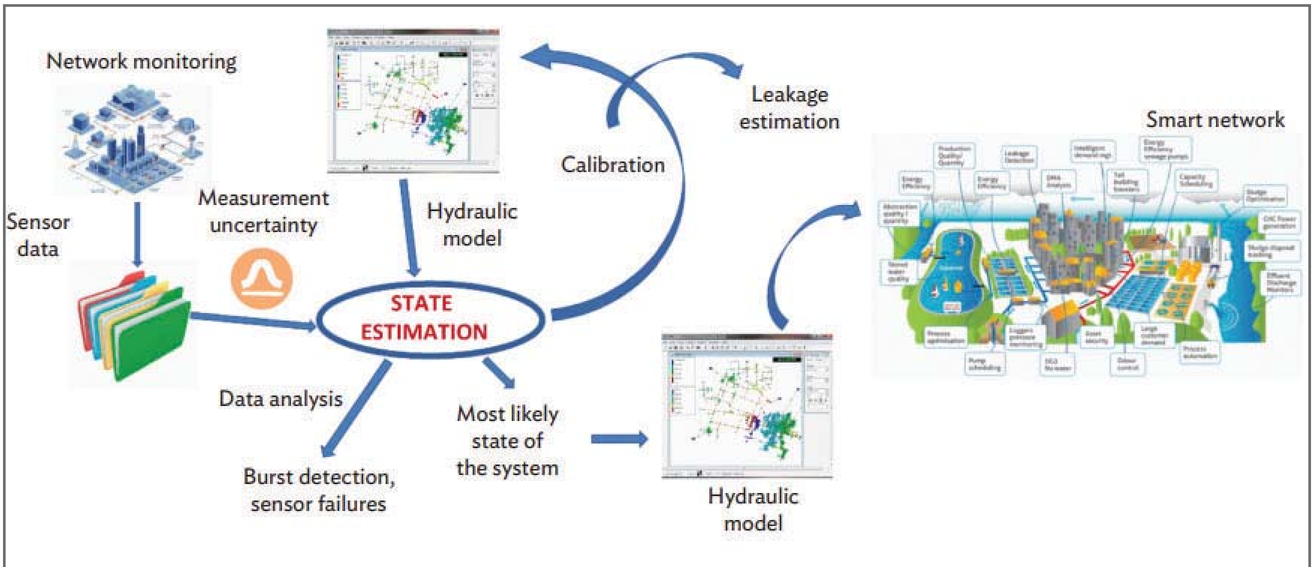
The digital transformation of the water supply sector plays a critical role in advancing the Sustainable Development Goals (SDGs), particularly SDG 6 (Ensure availability and sustainable management of water and sanitation for all) and SDG 13 (Climate Action), by driving investments aimed at mitigating the impacts of climate change.

The application of AI-driven tools in water management directly addresses several major global challenges in the sector:

1. **Aging Infrastructure and Budget Constraints:** AI can help manage aging and deteriorating water assets more effectively, optimizing both capital expenditures (CAPEX) and operating expenditures (OPEX), while minimizing the need for sharp increases in water tariffs.

9 https://efcnetwork.org/

Figure 2: Main Components of a Network Analysis System, Including Hydraulic Modelling 2.0 Functionalities



Source: Asian Development Bank brief, No 145, 2022

2. **Water as a Limiting Factor in the Water–Food–Energy Nexus:** As water becomes increasingly scarce and polluted—exacerbated by climate change and urbanization—AI technologies can support more efficient and sustainable allocation of water resources across sectors.
3. **Integrated Water Resources Management (IWRM):** AI tools can enhance IWRM strategies at both regional and urban levels, supporting the development of low-impact, climate-resilient infrastructure such as sponge cities.

In the context of reducing Unaccounted-for Water (UFW), traditional leak detection methods rely on specialized equipment—such as acoustic sensors and gas tracers—in combination with human expertise. However, a growing trend is the integration of artificial intelligence (AI) into these technologies (e.g., acoustic correlators), enabling automated interpretation of data such as leak noises, thereby reducing reliance on manual analysis. Furthermore, advances in numerical hydraulic modelling of water distribution networks now allow for the identification of potential leakage zones through data-driven simulations. These models can accurately detect suspect pipe segments—provided they are supported by robust, calibrated field data including pressure, flow rates, and node-level consumption[10].

The literature on Unaccounted-for Water (UFW) and Non-Revenue Water (NRW) highlights a growing body of research focused on leveraging data and big data from a variety of sources to enhance water loss detection and management. These efforts primarily involve:

- Cost-effective sensor technologies (e.g., pressure, flow, acoustic sensors) that provide real-time monitoring of water distribution systems;
- Calibrated hydraulic models that simulate the behaviour of water networks and help identify anomalies indicative of leaks or unauthorized usage; and
- Advanced numerical and AI-based techniques that process large volumes of data to predict, detect, and localize both physical losses (leaks) and commercial losses (meter inaccuracies, theft).

This integrated approach reflects a shift toward data-driven, predictive, and preventive water management strategies, enabling utilities to minimize losses, improve operational efficiency, and reduce costs.

Physically based methods in water management increasingly incorporate artificial intelligence (AI) to enhance operational efficiency and predictive capability. These approaches integrate statistical tools—such as state estimation techniques and

10 E. Caro, R. Mínguez, and A. J. Conejo. 2013. Robust WLS Estimator Using Reweighting Techniques for Electric Energy Systems. Electric Power Systems Research. 104. pp. 9–17.

pressure sensitivity analysis—with advanced hydraulic modelling. By leveraging the fundamental physical laws of mass and momentum conservation that govern water distribution networks, AI-enabled systems can interpret complex interactions within the network more accurately[11].

The integration of AI algorithms with real-time data and numerical models enables the creation of a digital twin or digital mirror of the physical water infrastructure. This allows water utilities to simulate, monitor, and optimize scenarios dynamically, thereby supporting proactive decision-making and advancing digital transformation in the sector[12].

Data-driven methods use AI and machine learning techniques like neural networks, support vector machines, decision trees, and adaptive neuro-fuzzy systems to analyse water systems. These tools can find patterns and detect issues like pipe bursts without needing complex hydraulic equations—once they are trained with large amounts of data.

However, these methods aren't always ideal for analysing water networks (like finding leaks, bursts, or unaccounted-for water) because most utilities don't have enough historical data to train the algorithms properly. Also, many things that affect water systems—like how people use water, illegal connections, and climate—are difficult to model with physics-based methods. Other issues, like pipe corrosion, joint wear, or soil pressure, involve complex processes that science doesn't fully understand yet.

This is where AI-driven approaches can help—by learning from data, they can provide insights where traditional models fall short. The future lies in combining both approaches—a hybrid method—that blends the accuracy of physical modelling with the power of AI and big data. This next step, known as Hydraulic Modelling 2.0, offers smarter tools for modern water utilities.

Integrating AI for Managing Unaccounted-for Water: Policy and Operational Implications

National water sector policies must evolve to support water utilities in their digital transformation by introducing updated technical guidelines and a structured roadmap. This transformation should enable efficient and cost-effective use of AI-driven numerical tools. Utilities currently using Hydraulic Modelling 1.0 and possessing digital data can now leverage advancements in artificial intelligence and big data analytics to enhance operational efficiency and customer service.

Piloting AI in conjunction with Hydraulic Modelling 2.0 for addressing UFW can demonstrate how advanced analytical tools improve network performance and service delivery. This also positions water utilities at the forefront of innovation by utilizing AI-powered insights drawn from SCADA systems and sensor-fed data across the water distribution network.

Key Benefits of Using AI Algorithms for Water Utilities:

1. **Real-Time Integration Simplified:** AI simplifies the process of connecting with digital systems in real time, removing technical complexities.
2. **Enhanced Data Analysis:** AI evaluates the performance of the water distribution network using a larger dataset than what real-time monitoring alone can capture—an advantage particularly useful during short pilot projects.
3. **Event Detection Capability:** AI algorithms validate their effectiveness by detecting past events such as pipe bursts or sensor failures, improving historical analysis.
4. **Comparative Accuracy:** AI enables direct comparisons between traditional UFW estimation methods and predictions made by intelligent algorithms, helping utilities benchmark and validate their results.

This AI-powered approach provides water utilities with a competitive edge, making their operations smarter, more efficient, and more responsive to both technical and environmental challenges.

IoT in Water Management

The Internet of Things (IoT) plays a transformative role in smart water management, particularly in agriculture. By enabling real-time monitoring of soil moisture, weather conditions, and crop requirements, IoT helps optimize

11 The International Benchmarking Network for Water and Sanitation Utilities (funded by the World Bank Group and the International Water Association with the support of other development partners and stakeholders) promotes good benchmarking practices among water and sanitation services. See International Benchmarking Network. https://www.ib-net.org/.

12 Low-impact development applied to sponge cities is a land planning and engineering design approach to manage stormwater as part of climate adaptation proofing of urban infrastructure. It emphasizes conservation and use of on-site-natural features to protect water quality.

irrigation practices through precision agriculture. This ensures that the right amount of water is delivered at the right time, significantly reducing water wastage while enhancing crop productivity. IoT systems also support automated and remote control of irrigation infrastructure, minimizing manual labor and improving operational efficiency. With the integration of various sensors and data analytics, farmers can make informed, data-driven decisions that lead to better resource management. Additionally, IoT-based systems can detect leaks, over-irrigation, and equipment malfunctions early, preventing unnecessary water loss. The use of cloud or fog computing further enhances scalability and system intelligence, making it adaptable to different farm sizes and conditions. Overall, IoT contributes not only to increased agricultural efficiency and cost savings but also to environmental sustainability by promoting the judicious use of water resources.

The Internet of Things (IoT) can significantly enhance groundwater management by enabling real-time monitoring, data collection, and smart decision-making. IoT sensors installed in wells, aquifers, and water distribution systems can continuously track groundwater levels, recharge rates, water quality, and extraction volumes. This real-time data helps identify trends, detect over-extraction, and prevent groundwater depletion. By integrating IoT with cloud platforms and data analytics, authorities can visualize usage patterns, forecast demand, and implement timely interventions. Moreover, IoT enables automated alerts in case of contamination, illegal drilling, or equipment malfunction, ensuring prompt corrective action. Through improved data availability and transparency, IoT also facilitates better coordination among stakeholders, supports policy-making, and promotes sustainable groundwater use across urban and rural settings.

Global Trends in the Use of AI in Water Management

1. **Real-Time Monitoring and Predictive Analytics:** AI is increasingly being used for real-time monitoring of water quality, availability, and distribution. Predictive models, using machine learning (ML) and deep learning (DL), forecast water demand, detect potential contamination, and anticipate droughts or floods—enabling pre-emptive action.
2. **Smart Irrigation Systems:** Precision agriculture supported by AI and IoT is becoming a global standard, especially in water-scarce regions. AI analyzes data from soil sensors, weather stations, and satellite imagery to determine optimal irrigation schedules, reducing water use and improving crop yields.
3. **Leak Detection and Non-Revenue Water Reduction:** In urban water supply systems, AI-powered tools analyse flow and pressure data to detect leaks, identify anomalies, and reduce non-revenue water (NRW). Countries like Singapore and Israel are leading in adopting such AI-integrated infrastructure.
4. **AI-Driven Water Quality Assessment:** AI models are used for rapid water quality testing by interpreting sensor and lab data. They can classify pollution sources and suggest treatment protocols. AI also aids in monitoring wastewater and surface water contamination in real time. Around 80% of wastewater globally is discharged without adequate treatment[13].
5. **Flood and Disaster Management:** AI is helping governments and disaster management authorities predict and manage flood risks through early warning systems. These models integrate satellite data, rainfall patterns, and hydrological models for accurate forecasting.
6. **Optimizing Water Treatment Operations:** AI is being adopted in wastewater treatment plants to optimize chemical dosing, energy use, and sludge management. Smart control systems based on AI reduce costs and increase operational efficiency.
7. **Decision Support Systems for Policymakers:** AI-based dashboards and simulation tools are being developed to assist in water governance. These systems help evaluate policy impacts, design water-saving strategies, and ensure equitable distribution of resources.
8. **Integration with Digital Twins:** Many utilities and municipalities are developing digital twins—virtual replicas of water systems—augmented by AI for scenario planning, infrastructure management, and predictive maintenance.
9. **Climate Resilience and Sustainability Planning:** AI is used to model long-term climate impacts on water availability, helping cities and regions develop adaptive strategies for sustainable water use under changing environmental conditions.

13 UNESCO WWAP, 2021

10. **Citizen Engagement and Education Tools:** AI-powered apps and platforms are being used to raise public awareness, provide customized water-saving tips, and involve communities in participatory water monitoring.

Innovation and R&D in the Jal Jeevan Mission

Har Ghar Jal
Jal Jeevan Mission

The Jal Jeevan Mission (JJM) not only focuses on delivering potable water to every rural household but also actively promotes innovation and research & development (R&D) to ensure long-term water security and sustainability. The mission encourages startups, research institutions, and technology providers to develop and deploy cost-effective, scalable, and context-specific solutions for water treatment, monitoring, and delivery. Through initiatives like pilot projects, hackathons, and innovation challenges, JJM facilitates the testing and adoption of new technologies such as real-time water quality sensors, automated chlorine dosing systems, solar-powered water pumps, and AI-powered analytics platforms. By creating a robust framework for collaboration between government agencies, academia, and the private sector, the mission ensures continuous improvement in service delivery. This forward-looking approach positions JJM as a catalyst for transforming India's water sector through technology-driven, evidence-based policymaking and implementation.

Machine Learning in Aquifer Monitoring and Groundwater Forecasting

Machine learning (ML) is playing a transformative role in aquifer monitoring and groundwater forecasting, offering powerful tools to model complex hydrological processes and predict groundwater trends with greater accuracy. Traditional methods often struggle with the non-linear, dynamic behaviour of aquifer systems, especially in regions with limited data. ML models—such as Random Forests, Support Vector Machines (SVM), Artificial Neural Networks (ANN), and Long Short-Term Memory (LSTM) networks—are increasingly used to analyse historical groundwater data, rainfall patterns, land use changes, and aquifer characteristics to predict water table levels and recharge rates. These models can identify hidden patterns, detect anomalies such as contamination or over-extraction, and provide early warnings of groundwater depletion. When integrated with real-time sensor networks and remote sensing data, ML enhances the spatial and temporal resolution of aquifer monitoring. This data-driven approach supports informed decision-making for sustainable groundwater management, especially in drought-prone or over-exploited regions.

India is the largest user of groundwater globally, extracting around 245 billion cubic meters annually, with over 60% of irrigation and nearly 85% of rural drinking water needs dependent on this vital resource. However, unsustainable extraction has led to severe stress, with groundwater levels declining in about 60% of wells monitored by the Central Ground Water Board (CGWB). Out of 6,965 assessed blocks across the country, over 1,100 are classified as over-exploited, where groundwater extraction exceeds recharge. States like Punjab, Haryana, Rajasthan, and Tamil Nadu are particularly affected, witnessing water table declines of up to 1 meter per year. Furthermore, groundwater quality is deteriorating, with high levels of arsenic, fluoride, iron, and nitrate affecting water safety in many regions. The national average stage of groundwater extraction stands at around 60%, with some states exceeding 100%, indicating critical stress. In response, the Government of India has launched initiatives like the Atal Bhujal Yojana and Jal Shakti Abhiyan to promote sustainable, community-led groundwater management and recharge.

Simplifying Water Audits and Encouraging Adoption in Cities

1. **Real-time Monitoring and Data Collection**

   IoT-enabled smart sensors installed on pipelines, water meters, storage tanks, and appliances can continuously collect real-time data on water flow, consumption, leakage, and pressure. This provides a comprehensive picture of water usage patterns across urban infrastructures.

2. **Leak Detection and Non-Revenue Water (NRW) Management**

   AI algorithms can analyse data from IoT devices to detect anomalies such as leaks, illegal connections, or unaccounted-for water. By identifying these early, utilities can minimize water loss and improve the efficiency of water delivery systems.

3. **Predictive Maintenance**

   Machine learning models can predict equipment failure or pipeline bursts based on historical and real-time data. This allows utilities to carry out maintenance before issues escalate, reducing downtime and costs.

4. **Automated Water Usage Audits**

   Instead of manual audits, AI systems can generate automated audit reports using IoT data. These reports can identify areas of overuse, inefficiencies, or non-compliance with water usage norms in residential, commercial, and industrial sectors.

5. **Behavioural Insights and Demand Forecasting**

   AI can identify consumption trends and predict future water demand based on weather patterns, occupancy rates, or usage history. This helps in demand-side management and better urban planning.

6. **Integration with GIS for Spatial Analysis**

   By combining AI and IoT with GIS (Geographic Information Systems), urban water auditors can visualize water use, leaks, and efficiency across different city zones, enabling targeted interventions.

7. **Sustainability and Water Neutrality Goals**

   Smart water audits powered by AI and IoT support cities in tracking their progress toward water conservation targets and water neutrality certification.

Conclusion

Emerging technologies in water harvesting, management, and recycling are playing a crucial role in advancing global efforts for water conservation. The integration of artificial intelligence (AI), particularly machine learning and deep learning, offers a promising path forward for the sustainable management of water resources. This study highlights key applications of water management that leverage modern deep neural network models, emphasizing their relevance and effectiveness across various processes. It also explores the challenges and opportunities associated with implementing deep learning in water management systems, including concerns related to data quality and availability, system security, context-aware data analysis, and training efficiency. Overall, the study provides valuable insights and outlines potential directions for future research aimed at enhancing water management through the application of advanced AI techniques.

In areas where water is scarce, managing this vital resource efficiently becomes a critical challenge in farming. This study therefore focuses on the question: How can artificial intelligence (AI) and the Internet of Things (IoT) contribute to precision agriculture to enhance sustainability through water conservation? IoT devices, such as soil moisture sensors and weather monitoring systems, collect real-time environmental data. AI algorithms then analyse this data to automate irrigation, estimate water consumption, and prevent overwatering. By evaluating both current and historical data through machine learning, the system can predict crop water needs and optimize irrigation schedules accordingly. Additionally, AI-driven analytics can identify potential irrigation issues and suggest corrective actions. This research demonstrates how combining IoT and AI technologies can improve decision-making in water management, reducing water depletion and over-irrigation. The framework also supports integrated soil nutrient management and conservation agriculture, enhancing sustainable agricultural productivity in water-scarce regions while increasing water use efficiency. Ultimately, the paper shows that the synergy between IoT and AI in precision agriculture can drive future water management strategies, leading to higher crop yields, more efficient resource use, and long-term sustainability.

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