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ORIGINAL RESEARCH

Water scarcity solutions via artificial intelligence and machine learning: A systematic review

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Abstract

Objective: Water scarcity and degradation of water quality pose significant global challenges, necessitating innovative solutions for effective water management. Artificial Intelligence (AI) has emerged as a powerful tool for optimizing water distribution, leak detection, desalination, treatment, and quality monitoring. This review examines AI-driven models, including machine learning and deep learning, that enhance predictive capabilities, facilitate continuous tracking, and support data-driven decision-making in water systems.
Materials and Methods: A comprehensive search was conducted in major databases, including PubMed, IEEE Xplore, Web of Science, and Scopus, using predefined keywords and Boolean operators to retrieve peer-reviewed studies published up to 2024. Relevant studies on AI in water management were selected, and the data were synthesized thematically.
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Results: Upon processing the available literature, 75 studies were selected for the final review. Results show that AI enhances predictive modelling in urban water distribution, demand forecasting, leak detection, and infrastructure maintenance. Integrating AI with Geographic Information Systems (GIS) and the Internet of Things (IoT) boosts spatial planning, anomaly detection, and operational efficiency. AI-driven smart irrigation systems and remote sensing optimize water allocation in agriculture. Moreover, AI improves runoff estimation, reservoir management, water quality assessment, desalination, wastewater treatment, and stormwater control
Conclusion: AI is revolutionizing water management by enhancing efficiency, sustainability, and resilience. To overcome current challenges, interdisciplinary collaboration, regulatory improvements, and technological advancements are essential.

Keywords: Artificial intelligence, Water insecurity, Water quality, Water supply, Machine learning, Deep learning, Neural networks, Computer, Environmental monitoring

Introduction

Water is essential for human life, preservation of environmental sustainability, and economic growth. However, population growth, climate change, and industrial expansion have placed immense pressure on global water resources, resulting in water scarcity, pollution, and inefficient distribution. In response to these concerns, the application of artificial intelligence (AI) in water management has garnered significant attention, offering data-driven solutions to refine resource distribution, enhance monitoring frameworks, and improve decision-making processes. AI-driven models, such as machine learning (ML) and deep learning (DL), have shown great potential in various aspects of water management, including urban water distribution, irrigation systems, drought prediction, desalination, wastewater treatment, and water quality monitoring. AI can enhance the efficiency, precision, and sustainability of water management strategies by using large datasets and employing advanced analytics. Urban water distribution systems face multiple challenges, such as leakages, infrastructure degradation, and fluctuating water demand. AI technologies, particularly predictive modeling and real-time anomaly detection, have been applied to address these issues. For example, Long Short-Term Memory (LSTM) networks and Supervisory Control and Data Acquisition (SCADA) data have been used in AI-based models to find leaks and plan maintenance for water distribution systems [1, 2]. Integrating AI with Geographic Information Systems (GIS) and the Internet of Things (IoT) has further enhanced spatial planning and automated monitoring, reducing non-revenue water losses and optimizing supply networks [3]. AI is revolutionizing irrigation management in agriculture by enhancing water-use efficiency and optimizing crop productivity. AI-powered Decision Support Systems (DSS) and IoT-enabled smart irrigation systems allow farmers to track real-time soil moisture, weather trends, and overall crop health [4, 5]. DL models, such as U-Net-Convolutional Long Short-Term Memory (UNet-ConvLSTM), have been applied to predict water demand and optimize irrigation scheduling, thereby reducing water wastage while ensuring sustainable agricultural practices [6, 7]. AI's ability to integrate remote sensing data with predictive analytics has further improved the precision of irrigation planning, contributing to increased agricultural resilience in water-scarce regions. AI can also significantly influence drought and weather forecasting by utilizing vast meteorological and hydrological datasets. AI models, such as hybrid AutoRegressive Integrated Moving Average (ARIMA) and Support Vector Regression (SVR), have been utilized to enhance the accuracy of Standardized Precipitation Index (SPI) forecasts. This gives drought-prone areas early warnings [8, 9]. Similarly, AI-driven automation in wastewater treatment plants optimizes regulatory compliance, chemical dosing, and pollutant removal [10, 11]. These AI-driven approaches enhance decision-making for water authorities and policymakers, enabling them to implement proactive measures that mitigate the impacts of drought. Desalination and wastewater treatment are essential for securing clean and potable water, particularly in arid and semi-arid regions. AI technologies have been applied to optimize desalination plant operations by improving membrane fouling detection, predicting energy consumption, and enhancing system performance [12, 13]. The use of AI in real-time water quality monitoring through satellite-based models and remote sensors has further strengthened pollution detection and contamination prevention efforts [14, 15]. Challenges persist in the widespread adoption of AI in water management despite the numerous benefits it offers. Data heterogeneity, computational constraints, and infrastructure limitations present barriers to AI implementation, particularly in developing regions [16, 17]. Additionally, concerns over cybersecurity, information confidentiality, and the interpretability of AI models must be addressed to ensure accountability and foster trust in AI-driven water governance [18, 19]. Future research should enhance AI model adaptability, integrate AI with smart city initiatives, and develop standardized policies for ethical and sustainable AI deployment in water management. This review explores the latest advancements in AI applications for water distribution, irrigation, drought prediction, desalination, wastewater treatment, and quality monitoring. Earlier reviews have examined specific areas, including climate resilient water management using LSTM and hybrid models [20], AI-based assessment of

water consumption [21], and AI techniques for detecting leaks, predicting demand, and monitoring quality [22]. However, these studies tended to focus on single aspects or regions. A comprehensive, cross-sectoral synthesis that integrates these themes remains lacking. This paper aims to fill that gap by analyzing recent studies to provide a unified perspective on AI's potential to revolutionize water management and identify major issues that must be solved for successful integration. The findings underscore the importance of an interdisciplinary approach and ongoing investment in AI research to ensure sustainable and resilient water systems for future generations.

Materials and Methods

Study sample

We conducted this systematic review in accordance with the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and registered it in the PROSPERO International Prospective Register of Systematic Reviews (Registration ID: CRD420250655265). The primary focus areas included AI applications in urban water distribution, irrigation systems, drought prediction, desalination, wastewater treatment, and water quality monitoring. Furthermore, challenges in integrating AI solutions into existing water management infrastructures were also explored. The search strategy was based on predefined research questions and applied Boolean logic to refine the selection of relevant studies. The main research questions guiding this review were:

1. How can AI and ML improve predictive modelling for drought forecasting and water scarcity management?
2. What are the major applications of AI-driven systems regarding optimizing water resource management, such as smart irrigation and urban water distribution networks?
3. What challenges hinder the application of AI solutions in existing water management infrastructures, and how should these challenges be addressed?

To answer these questions, four academic databases were searched for peer-reviewed studies: PubMed, IEEE Xplore, Web of Science, and Scopus.

2.1. Inclusion and Exclusion Criteria

Studies that met the following criteria were included:

- Focused on AI-driven solutions for water management, including predictive modelling, leak detection, irrigation, water treatment, and quality monitoring.
- Published in either peer-reviewed journals or conference proceedings.
- Provided empirical evidence, case studies, or experimental results demonstrating AI applications in water systems.
- Addressed challenges related to AI adoption in water infrastructure, such as data limitations, cost barriers, and scalability.

Studies were excluded based on the following criteria:

- Did not directly focus on AI applications in water management.
- Were review articles, opinion papers, or editorials without original research contributions.
- Focused solely on theoretical AI models without practical application to water management.
- Were published in non-English languages.

2.2. Data Extraction and Analysis

For each selected study, relevant data—including study objectives, AI methodologies used, key findings, and challenges identified—were independently extracted by two reviewers to ensure accuracy and reduce bias. The extracted data were categorized based on their focus areas:

- Urban Water Distribution and Leak Detection
- Smart Irrigation and Agricultural Water Management
- Drought Prediction and Weather Forecasting

- Desalination and Wastewater Treatment
- Water Quality Monitoring and Pollution Control
- Challenges in AI Integration and Scalability

A qualitative synthesis was conducted to compare AI techniques, highlight trends in AI-driven water management, and identify existing gaps in research. The review also assessed the applicability of AI models across different geographical and climatic contexts.

2.3. Data Synthesis

The data synthesis followed a qualitative thematic analysis approach. The findings of multiple studies were integrated to thoroughly demonstrate AI's role in water management. Prior to synthesis, the methodological quality of the included studies was independently assessed by two reviewers using standardized tools appropriate to each study type—namely, the Critical Appraisal Skills Programme (CASP) checklists for qualitative and observational studies, and the Joanna Briggs Institute (JBI) critical appraisal tools for experimental and quasi-experimental designs. Discrepancies were resolved through discussion or consultation with a third reviewer. Studies were grouped based on their research focus, and their methodologies, results, and limitations were analyzed collectively. The synthesis process aimed to:

- Identify the most commonly used AI techniques in water management.
- Compare the effectiveness of AI-driven solutions across different water management applications.
- Highlight the benefits and challenges of AI integration in various environmental and infrastructural settings.

The studies were analyzed to assess the role of AI in improving water resource management and its implications for future research and policy. Trends in AI adoption, scalability, and real-world implementation were also examined. Findings were summarized using a narrative synthesis approach, highlighting critical gaps, such as data accessibility, infrastructure readiness, and ethical considerations in AI deployment.

Results

3.1. Overview

This review followed the PRISMA guidelines for transparency and rigor. We began by identifying 537 records from database searches. After removing duplicates, 512 records remained. Following the title review, 275 records were retained, while 237 were excluded. After the abstract screening, 245 records remained, and 30 were excluded. A full-text review was conducted on 80 studies, of which 162 were excluded. Additionally, five records were removed due to data overlap. Ultimately, 75 studies were included in the final review (Figure 1).

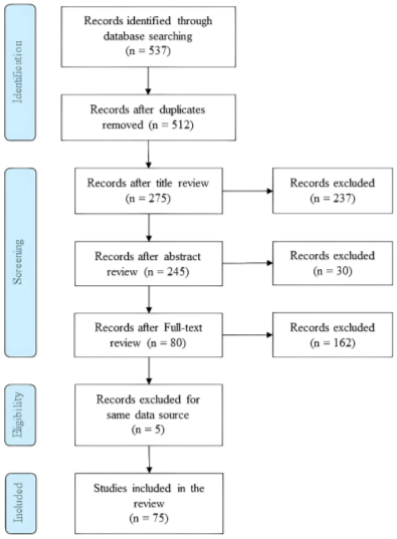


Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram of study selection.

Table 1 shows a summary of the primary findings from the selected studies. The data include details on study characteristics, participant demographics, and the main outcomes assessed.

	AUTHORS	COUNTRY	STUDY TITLE	QUALITY	STUDY DESIGN	INTERVENTION METHOD	TOT_N	N	AGE	N	AGE	COMPARISON	OUTCOME
1	Sadiki & Jang (2024)	South Korea	Estimation of Hydraulic and Water Quality Parameters Using Long Short-Term Memory in Water Distribution Systems	Good	Experimental	LSTM-based prediction of hydraulic and water quality parameters	N/A	N/A	N/A	N/A	N/A	Traditional hydraulic modeling vs. LSTM approach	LSTM improves the prediction accuracy of hydraulic behavior and water quality in distribution networks
2	Schaeffer et al. (2024)	USA	Forecasting Freshwater Cyanobacterial Harmful Algal Blooms for Sentinel-3 Satellite Resolved U.S. Lakes and Reservoirs	Good	Observational	INLA with Sentinel-3 data	2,192 lakes	Weekly cyanobacteria abundance data	N/A	N/A	N/A	INLA vs. ML-based forecasting methods	INLA model outperforms ML models, achieving 90% prediction accuracy
3	Shah et al. (2024)	Pakistan	Application of RNN-LSTM in Predicting Drought Patterns in Pakistan: A Pathway to Sustainable Water Resource Management	Fair	Observational	RNN-LSTM for drought prediction	N/A	N/A	N/A	N/A	N/A	RNN-LSTM vs. traditional meteorological models	Improved predictive accuracy for drought patterns and water resource planning
4	Taylan (2024)	Türkiye	An Approach for Future Droughts in Northwest Türkiye: SPI and LSTM Methods	Fair	Observational	SPI with LSTM-based forecasting	N/A	N/A	N/A	N/A	N/A	SPI vs. SPI-LSTM models	LSTM enhances long-term drought forecasting reliability
5	Ye et al. (2024)	China	AI-driven Optimization of Agricultural	Good	Experimental	12Net-ConvLSTM model integrating	N/A	N/A	N/A	N/A	N/A	12Net-ConvLSTM vs. traditional	The AI-driven model improves irrigation efficiency, achieving

			Water Management for Enhanced Sustainability			remote sensing and AI for irrigation optimization						forecasting models	R²=0.927 (MODIS) and R²=0.935 (OLDAS)	
6	Qiu et al. (2024)	China	Multiple Types of Missing Precipitation Data Filling Based on Ensemble Artificial Intelligence Models	Good	Experimental	AI-based ensemble models for filling missing precipitation data	N/A	N/A	N/A	N/A	N/A	AI ensemble models vs. traditional statistical imputation methods	AI ensemble models effectively reconstruct missing precipitation data with improved accuracy and reduced uncertainty	
7	Rahaman et al. (2024)	Global	Privacy-Centric AI and IoT Solutions for Smart Rural Farm Monitoring and Control	Good	Experimental	AI-based security framework for IoT data protection in smart farming	N/A	N/A	N/A	N/A	N/A	AI-enhanced security protocol vs. conventional IoT security measures	Enhanced data protection, reduced cyber-attack risks, and improved performance with a computation time of 0.04s for 11 messages	
8	Rajitha et al. (2024)	Sri Lanka	Machine Learning and AI-Driven Water Quality Monitoring and Treatment	Fair	Observational	AI-based models for real-time water quality monitoring and treatment optimization	N/A	N/A	N/A	N/A	N/A	AI-based models for real-time water quality monitoring and treatment optimization	AI improves real-time monitoring, optimizing treatment efficiency and ensuring compliance with water quality standards.	
9	Ramoyha et al. (2024)	Global	The Potential of Stormwater Management Strategies and Artificial Intelligence Modeling Tools to Improve Water Quality: A Review	Good	Systematic Review	AI applications in stormwater management and water quality improvement	N/A	N/A	N/A	N/A	N/A	AI-based stormwater models vs. traditional stormwater management strategies	AI enhances stormwater management by improving predictive accuracy and pollution mitigation strategies.	
10	Rozhkov a et al. (2024)	India	Improving the Efficiency of Water Use in Agriculture by Modelling the Classification of Groundwater Quality	Fair	Observational	AI-driven classification models for groundwater quality assessment in agriculture	N/A	N/A	N/A	N/A	N/A	AI-based groundwater quality classification vs. conventional assessment methods	AI enhances efficiency in groundwater classification, supporting optimized water use in agriculture.	
11	Joseph et al. (2024)	Australia	Leak and Burst Detection in Water Distribution Network Using Logic- and Machine Learning-Based Approaches	Good	Experimental	Machine learning and logic-based models for leak and burst detection in water distribution networks	N/A	N/A	N/A	N/A	N/A	ML-based leak detection vs. traditional water network monitoring	ML-based approaches enhance leak detection accuracy and response time, reducing water loss and infrastructure damage	
12	Kang & Byun (2024)	South Korea	Development of a Multi-Scale Groundwater Drought Prediction Model Using Deep Learning and Hydrometeorological Data	Good	Observational	Deep learning-based groundwater drought prediction using hydrometeorological datasets	N/A	N/A	N/A	N/A	N/A	Deep learning-based groundwater drought prediction vs. traditional statistical models	The AI-driven model improves prediction accuracy for groundwater droughts, supporting proactive water resource management.	
13	Momin et al. (2024)	Global	Artificial Intelligence for Water Consumption Assessment: State of the Art Review	Good	Systematic Review	AI-based models for water consumption prediction and assessment	N/A	N/A	N/A	N/A	N/A	AI-based water consumption analysis vs. conventional assessment methods	AI enhances water consumption assessment accuracy, facilitating improved resource allocation and conservation strategies	
14	Nash et al. (2024)	Global	Internet of Things-Based Automated Solutions Utilizing Machine Learning for Smart and Real-Time Irrigation Management: A Review	Good	Systematic Review	IoT-integrated ML solutions for automated irrigation management	N/A	N/A	N/A	N/A	N/A	Automated irrigation systems vs. traditional irrigation management	IoT and ML-driven irrigation systems improve efficiency, enhance crop yield, and reduce water waste through optimized irrigation scheduling	
15	Olentsov a et al. (2024)	India	Predictive Modelling of Post-Monsoon Groundwater Quality in Telangana Using Machine Learning Techniques	Fair	Observational	ML-based predictive modeling for post-monsoon groundwater quality assessment	N/A	N/A	N/A	N/A	N/A	AI-driven groundwater quality prediction vs. conventional assessment methods	AI enhances the accuracy of groundwater quality classification, thereby aiding in agricultural and municipal water management.	
16	Esposito & Calabrò (2024)	Italy	Artificial Intelligence for Sustainable Water Resources Management. Case Study: Gorgovivo, Ascoli	Good	Case Study	AI-driven strategies for sustainable water resource management	N/A	N/A	N/A	N/A	N/A	AI-based water management vs. conventional resource management approaches	AI-enhanced water resource management improves efficiency, sustainability, and adaptive decision-making in water distribution systems	
17	Ferreira et al. (2024)	Global	Sustainable Water Management in Horticulture: Problems, Promises, and Promises	Good	Systematic Review	AI and technology-driven sustainable water management practices in horticulture	N/A	N/A	N/A	N/A	N/A	AI-assisted horticultural water management vs. traditional irrigation and resource use strategies	AI-driven approaches enhance water conservation, optimize irrigation, and improve sustainability in horticultural production.	
18	Garofalo et al. (2024)	Mediterranean Basin	Predicting Carob Tree Physiological Parameters Under Different Irrigation Systems Using Random Forest and Planet Satellite Images	Good	Experimental	Machine learning (RF) and remote sensing for predicting carob tree physiological parameters under varying irrigation conditions	N/A	N/A	N/A	N/A	N/A	RF vs. traditional multiple linear regression for physiological parameter prediction	RF models achieved high accuracy ($R^2 = 0.81$ for net assimilation and $R^2 = 0.70$ for stomatal conductance), demonstrating AI's potential in precision agriculture and irrigation planning.	
19	Goh et al. (2024)	Malaysia , China	Expediting Decarbonization in Energy, Waste, and Water Sector Through Digitalization in the energy, waste, and water sectors	Good	Case Study	Digitalization and AI-driven Industry 5.0 solutions for decarbonization in the energy, waste, and water management	N/A	N/A	N/A	N/A	N/A	Digitalization-driven sustainability strategies vs. conventional approaches in energy, waste, and water management	AI and digital technologies improve efficiency, reduce emissions, and optimize resource use in smart city infrastructure.	
20	Hameed et al. (2024)	Malaysia	SSC: Case-Studies in Malaysia and China Based on Industry 5.0 Paradigm	Good	Experimental	Hybrid RELM-SO vs. LSTM for drought forecasting	58 years of streamflow data from two stations	N/A	N/A	N/A	N/A	RELM-SO model vs. LSTM and classical statistical models for drought forecasting	RELM-SO outperforms LSTM with lower RMSE (0.1413 at station S1, 0.1211 at station S2) and higher prediction accuracy, improving long-term drought forecasting reliability	
21	Alex et al. (2024)	Global	Deep Learning Versus Hybrid Regularized Extreme Learning Machine for Multi-Month Drought Forecasting: A Comparative Study and Trend Analysis in Tropical Region	Good	Experimental	AI-governed valve regulation system for optimizing water distribution in piped and micro irrigation networks	N/A	N/A	N/A	N/A	N/A	AI-based intelligent valve regulation vs. conventional irrigation systems	AI-driven valve control improves irrigation efficiency, reducing water waste and optimizing agricultural water use	
22	Anandan et al. (2024)	Global	AI-Driven Smart Irrigation: Enhancing Agricultural Water Efficiency Through Intelligent Valve Regulation in Piped and Micro Irrigation Networks	Good	Experimental	IoT-based early warning system integrating SVM for drought prediction	N/A	N/A	N/A	N/A	N/A	IoT-SVM model vs. conventional drought forecasting methods	AI-enhanced early warning system improves drought prediction accuracy, supporting proactive water resource management	
23	Bragança et al. (2024)	Global	Enhanced Water Security and Resilience in Drought-Prone Zones with IoT and SVM Classifier for Early Warning Systems	Good	Systematic Review	AI-driven irrigation management	N/A	N/A	N/A	N/A	N/A	AI-integrated renewable irrigation vs.	AI-driven irrigation enhances sustainability, optimizes water use, and	
24	Elshaikh et al. (2024)	Global	integrating renewable energy in vineyard agriculture	Good	Systematic Review	AI models for optimizing precision irrigation techniques	N/A	N/A	N/A	N/A	N/A	AI-driven precision irrigation vs. conventional irrigation methods	traditional vineyard irrigation methods	improves energy efficiency in vineyard management.
25	Elnaki & Al-Mahish (2024)	Saudi Arabia	Applications of Artificial Intelligence in Precision Irrigation	Good	Observational	BVAR model for assessing water management impact on food security	2000–2020 data period	N/A	N/A	N/A	N/A	Water use efficiency impact on food insecurity vs. conventional agricultural water management	AI improves irrigation scheduling, enhances water conservation, and increases crop yields through precision water management	
26	Ahmad et al. (2024)	Global	Food Insecurity and Water Management Shocks in Saudi Arabia: Bayesian VAR Analysis	Good	Systematic Review	AI applications in agriculture, including crop surveillance, irrigation management, yield forecasting, and decision support systems	N/A	N/A	N/A	N/A	N/A	AI-driven agricultural solutions vs. traditional farming methods	Efficient water management can reduce food insecurity in the short term, with BVAR forecasting improved water-use strategies to enhance food security.	
27	Al Mashhadany et al. (2024)	Global	AI Can Empower Agriculture for Global Food Security: Challenges and Prospects in Developing Nations	Good	Experimental	I-integrated IoT systems for real-time environmental monitoring and automated irrigation management	N/A	N/A	N/A	N/A	N/A	AI-IoT-based irrigation monitoring vs. conventional irrigation practices	AI and IoT improve water use efficiency, optimize irrigation schedules, and enhance sustainability in agriculture	
28	Aldarwi, et al. (2024)	Iraq	Irrigation Intelligence: Enabling a Cloud-Based Internet of Things Approach for Enhanced Water Management in Agriculture	Good	Observational	AI-driven energy demand and supply forecasting using	2019–2021 dataset from the Iraq	N/A	N/A	N/A	N/A	AI-based forecasting models vs. traditional	AI improves electricity demand and supply forecasting, aiding energy	
			Addressing Energy Challenges in Iraq: Forecasting Power Supply and Demand Using Artificial Intelligence Models			multiple machine learning models (Linear Regression, XGBoost, RF, LSTM, Temporal Convolutional Networks, and Multi-Layer Perceptron)	Ministry of Electricity					energy forecasting techniques	security, policy-making, and economic development
29	Rahman et al. (2023)	Bangladesh	Smart Crop Cultivation System Using Automated Agriculture Monitoring Environment in the Context of Bangladesh Agriculture	Good	Experimental	IoT-integrated smart agriculture system with data mining and cloud monitoring for real-time crop forecasting	N/A	N/A	N/A	N/A	N/A	IoT-based smart farming vs. traditional agriculture methods	IoT-driven system improves agricultural productivity with 87.38% accuracy in data harvest prediction, supporting better decision-making for farmers	
30	Rezaqi & Shafiei (2023)	Afghanistan	Drought Forecasting Using W-ARIMA Model with Standardized Precipitation Index	Fair	Experimental	W-ARIMA model for drought prediction using the SPI	N/A	N/A	N/A	N/A	N/A	W-ARIMA model vs. traditional drought forecasting techniques	W-ARIMA enhances drought prediction accuracy, providing valuable insights for water resource management and climate adaptation	
31	Doulgeri s et al. (2023)	Global	A Comprehensive Survey of Machine Learning Methodologies with Emphasis in Water Resources Management	Good	Systematic Review	Overview of machine learning applications in water resource management, including hydrological modeling, drought forecasting, and water quality monitoring	N/A	N/A	N/A	N/A	N/A	Various ML methodologies applied in water management vs. traditional hydrological approaches	ML enhances predictive modeling, decision-making, and resource optimization in water resource management.	
32	Hameed et al. (2023)	USA, Canada	Machine Learning Models Development for Accurate Multi-Months Ahead Drought Forecasting: Case Study of the Great Lakes, North America	Good	Experimental	Development of hybrid drought forecasting models (SVR-BWO, RF-BWO, ELM-BWO, RELM-BWO) using the MBWI	1920–2020 dataset of lake water levels	N/A	N/A	N/A	N/A	Hybrid ML models with BWO vs. traditional drought forecasting models	RELM-BWO model achieved the highest accuracy, improving drought forecast reliability for up to six months ahead, benefiting policymakers and water managers	
33	Jang et al. (2023)	South Korea	RT-CLAD: Artificial Intelligence-Based Real-Time Chironomid Larva Detection in Drinking Water Treatment Plants	Good	Experimental	An AI-powered real-time detection system (RT-CLAD) for chironomid larvae in drinking water using CNN, YOLO, and ResNet models	N/A	N/A	N/A	N/A	N/A	CNN, YOLO, and ResNet models for larvae detection vs. conventional monitoring methods	The CNN-based RT-CLAD system achieved 100% accuracy and faster processing, thereby improving the security and safety of water treatment plants.	
34	Kannan et al. (2023)	Global	Exploring Ethical Dimensions of Environmental Sustainability and Use of AI	Good	Systematic Review	Ethical analysis of AI applications in environmental sustainability, focusing on transparency, accountability, and governance	N/A	N/A	N/A	N/A	N/A	Ethical considerations in AI for sustainability vs. unregulated AI deployment	AI-driven sustainability solutions must address ethical concerns such as data bias, decision-making accountability, and equitable resource distribution.	
35	Makropou lias & Rozakis (2023)	Greece	Artificial Intelligence for Decentralized Water Systems: A Smart Planning Agent Based on Reinforcement Learning for Off-Grid Camp Water Infrastructures	Good	Experimental	AI-based reinforcement learning system for optimizing decentralized water systems in off-grid camp environments	N/A	N/A	N/A	N/A	N/A	Reinforcement learning-based water system management vs. traditional off-grid water planning.	AI-driven smart planning agents enhance water distribution efficiency and sustainability in decentralized and emergency camp settings.	
36	Achite et al. (2023)	Global	An Election Algorithm Combined with Support Vector	Good	Experimental	Hybrid election algorithm and SVR for hydrological drought estimation	N/A	N/A	N/A	N/A	N/A	Hybrid SVR model vs. traditional drought estimation techniques	AI-enhanced drought estimation improves predictive accuracy and enables more efficient	
37	Awais et al. (2023)	Global	Regression for Estimating Hydrological Drought AI and Machine Learning for Soil Analysis: An Assessment of Sustainable Agricultural Practices	Good	Systematic Review	AI, DL, and ML for soil texture and SWC analysis	N/A	N/A	N/A	N/A	N/A	AI-based soil analysis vs. traditional statistical tools for soil assessment	water resource management AI-driven models provide faster, more accurate, and noise-free soil texture and SWC analysis, thereby enhancing smart irrigation and sustainable land management.	
38	Rozanad ani (2023)	Global	Optimal Water Management Strategies: Paving the Way for Sustainability in Smart Cities	Good	Systematic Review	AI and IoT-based water management strategies for smart cities	N/A	N/A	N/A	N/A	N/A	AI-based water management vs. conventional urban water strategies	AI-driven smart city water management improves resource efficiency, sustainability, and real-time decision-making	
39	Verma & Jain (2022)	Global	Digital Water	Good	Book Chapter / Review	AI and IoT applications for sustainable water resource management	N/A	N/A	N/A	N/A	N/A	AI-powered digital water management vs. traditional water governance models	AI- and IoT-based digital water systems enhance efficiency, automation, and predictive analytics, leading to improved water sustainability.	
40	Xiao et al. (2022)	China	Integration of Hydrological Model and Time Series Model for Improving the Runoff Simulation: A Case Study on BTOP Model in Zhou River Basin, China	Good	Experimental	Hybrid hydrological and time series modeling (BTOP and ARIMA-LSTM) for runoff simulation	N/A	N/A	N/A	N/A	N/A	AI-enhanced hydrological modeling vs. conventional runoff prediction models	AI-based models improve runoff simulation accuracy, enabling better flood predictions and water resource planning.	
41	Mishra et al. (2022)	Global	AdaBuzi 3D Based Smart Irrigation System Using MQTT	Good	Experimental	IoT-based smart irrigation system using AdaBuzi 3D and MQTT protocol for real-time water management in urban farming	N/A	N/A	N/A	N/A	N/A	IoT-integrated smart irrigation vs. conventional irrigation systems	AI-IoT-enabled irrigation system optimizes water use, reduces wastage, and improves efficiency in urban farming	
42	Panganib an et al. (2022)	Philippines	Protocol for Urban Farming An Urban Water Infrastructure Management System Design with Storm Water Intervention for Smart Cities	Good	Experimental	AI and GIS-based urban water infrastructure management with stormwater optimization for smart cities	N/A	N/A	N/A	N/A	N/A	AI-integrated water infrastructure management vs. traditional stormwater management	The AI-driven system improves stormwater management, enhances flood resilience, and optimizes urban water distribution.	
43	Serban et al. (2022)	Romania	Surface Water Change Detection via Water Indices and Predictive Modeling Using Remote Sensing Imagery: A Case Study of Nantai-Tuzla Lake, Romania	Good	Observational	Remote sensing and predictive modeling for detecting surface water changes in lakes	N/A	N/A	N/A	N/A	N/A	AI-enhanced water change detection vs. traditional remote sensing techniques	AI and predictive modeling improve surface water monitoring, enabling better conservation and management strategies.	
44	Sheng et al. (2022)	China	Key Technologies and Applications of Safety Diagnosis and Smart Management of Reservoir Dams	Good	Experimental	AI and IoT-based smart monitoring system for reservoir dam safety diagnostics	N/A	N/A	N/A	N/A	N/A	AI-driven dam safety management vs. traditional monitoring methods	AI improves early warning systems for dam failures, enhances predictive maintenance, and strengthens water infrastructure resilience	
45	Silva (2022)	Global	Implementation and Integration of Sustainability in the Water Industry: A Systematic Literature Review	Good	Systematic Review	AI and IoT integration for sustainable water industry practices	N/A	N/A	N/A	N/A	N/A	AI-driven sustainability strategies vs. conventional water management approaches	The integration of AI and IoT enhances sustainability, improves efficiency, and optimizes resource utilization in the water industry.	
46	Humphri es et al. (2022)	Pakistan	Runoff Estimation Using Advanced Soft Computing Techniques: A Case Study of Mangla Watershed	Good	Experimental	Soft computing models (ML-based) for runoff estimation in the Mangla watershed	N/A	N/A	N/A	N/A	N/A	AI-driven runoff estimation vs. conventional hydrological modeling	AI-based models improve runoff prediction accuracy, aiding better water resource management in the Mangla watershed	
47	Joseph et al. (2022)	Global	Watershed Pakistan Development of an Intelligent Urban Water Network System	Good	Experimental	AI-integrated urban water network system for optimizing water distribution and leak detection	N/A	N/A	N/A	N/A	N/A	AI-based urban water network optimization vs. traditional infrastructure monitoring	AI enhances leak detection, predictive maintenance, and water distribution efficiency in urban settings.	
48	Kim et al. (2022)	Global	OneMap Drought Monitoring Analysis Based on Statistical Models	Good	Observational	Statistical modeling for drought monitoring using the OneMap framework	N/A	N/A	N/A	N/A	N/A	OneMap-based drought prediction vs. traditional statistical drought analysis	AI-integrated statistical models improve drought monitoring accuracy, supporting proactive water resource management.	
49	Li et al. (2022)	China	Dissolved Oxygen Control Strategies for Water Treatment: A Review	Good	Systematic Review	AI and advanced control strategies for optimizing DO levels in WWTPs	N/A	N/A	N/A	N/A	N/A	AI-based DO control (PID, model-based predictive control, fuzzy logic, neural networks) vs. conventional DO control methods.	AI-enhanced DO control strategies improve accuracy, save aeration energy, and optimize nitrogen removal in WWTPs	
50	Liu et al. (2022)	China	Predicting Groundwater Indicator Concentration Based on Long Short-Term Memory Neural Network: A Case Study	Good	Experimental	LSTM neural network for predicting groundwater quality indicators (TDS, fluoride, nitrate, phosphate, metasilicate)	Groundwater monitoring data from 2000–2014	N/A	N/A	N/A	N/A	LSTM-based groundwater quality prediction vs. conventional statistical models	LSTM improves groundwater quality prediction accuracy, enabling early warnings and proactive resource management	
51	Achite et al. (2022)	Global	Exploring Bayesian Model Averaging with Multiple ANNs for Meteorological Drought Forecasting	Good	Experimental	BMA with ANNs for meteorological drought forecasting	N/A	N/A	N/A	N/A	N/A	BMA-ANN model vs. traditional meteorological drought	BMA-ANN improves drought forecast accuracy and reduces uncertainty in meteorological predictions	

			Drought Forecasts								forecasting models	
15	Alamoo et al.(2021)	Global	Simple Hydro-Economic Tools for Supporting Small Water Supply Agencies on Sustainable Irrigation Water Management	Good	Observational	Hydro-economic modeling for optimizing irrigation water management in small water supply agencies	N/A	N/A	N/A	N/A	N/A	Hydro-economic models vs. conventional irrigation water management methods	AI-driven hydro-economic models improve the cost-effectiveness and sustainability of irrigation water management
16	Badidi (2022)	Global	Edge AI and Blockchain for Smart Sustainable Cities: Promise and Potential	Good	Systematic Review	AI and blockchain integration for smart city water and resource management	N/A	N/A	N/A	N/A	N/A	AI, blockchain-based smart city management vs. traditional urban sustainability strategies	AI and blockchain improve data security, transparency, and resource efficiency in smart city infrastructures.
17	Hamal et al. (2022)	Global	Bibliometric Mapping of Trends, Applications, and Challenges of Artificial Intelligence in Smart Cities	Good	Systematic Review	AI bibliometric mapping for analyzing trends and challenges in smart city water and environmental management	N/A	N/A	N/A	N/A	N/A	AI-driven smart city research trends vs. traditional urban planning studies	AI enhances urban sustainability but requires improved governance, ethical considerations, and interdisciplinary collaboration.
18	Zia et al. (2021)	Pakistan	An Experimental Comparison of IoT-Based and Traditional Irrigation Scheduling on a Flood-Irrigated Subtropical Lemon Farm	Good	Experimental	IoT-based irrigation system with DSS for water optimization in subtropical lemon farming	2-acre farm test site over 9 months	IoT-based irrigation system	N/A	Traditional irrigation site	N/A	IoT-based irrigation scheduling vs. conventional flood irrigation	IoT-enabled irrigation reduced water use by ~50% and increased crop yield by 33% compared to traditional flood irrigation
19	Park et al. (2021)	Kyrgyzstan	Development of Earth Observational Diagnostic Drought	Good	Experimental	Earth observational satellite data combined with AI-driven	N/A	N/A	N/A	N/A	N/A	AI-based diagnostic drought prediction vs. traditional	AI-enhanced models improve regional drought forecasting, allowing better
			Prediction Model for Regional Error Calibration: A Case Study on Agricultural Drought in Kyrgyzstan			diagnostic models for drought prediction						regional meteorological models	preparedness and mitigation strategies.
15	Wang et al. (2021)	China	Analyzing the Adoption Challenges of the Internet of Things (IoT) and Artificial Intelligence (AI) for Smart Cities in China	Good	Systematic Review	Analysis of IoT and AI adoption barriers in smart city infrastructure and water management	N/A	N/A	N/A	N/A	N/A	AI-IoT-based smart city management vs. conventional urban infrastructure management	Challenges such as data privacy, interoperability, and regulatory gaps hinder AI-IoT integration, requiring policy interventions for effective implementation.
20	Wang et al. (2021)	China	Regional Suitability Prediction of Soil Salinization Based on Remote-Sensing Derivatives and Optimal Spectral Index	Good	Experimental	AI-enhanced remote sensing analysis using Landsat 8 OLI and Sentinel-2A MSI for soil salinity prediction	N/A	N/A	N/A	N/A	N/A	AI-driven spectral index-based soil salinity prediction vs. conventional remote sensing techniques	AI-based predictive modeling improves soil salinization mapping, supporting better environmental and agricultural land management.
21	Wong et al. (2021)	USA	Multiscale Assessment of Agricultural Consumptive Water Use in California's Central Valley	Good	Observational	AI and remote sensing-based evapotranspiration estimation using Landsat satellite data	30-m daily evapotranspiration estimates across California's Central Valley	Major irrigated crops (alfalfa, almond, citrus, corn, pasture, rice)	N/A	N/A	N/A	AI-based evapotranspiration modeling vs. field measurement-based estimates	AI-driven water use assessment improves understanding of crop water consumption, aiding sustainable groundwater and irrigation management
22	Xiang et al. (2021)	China	Urban Water Resource Management for Sustainable Environment Planning Using Artificial Intelligence Techniques	Good	Systematic Review	AI applications in urban water resource planning and sustainability	N/A	N/A	N/A	N/A	N/A	AI-based urban water resource management vs. traditional planning strategies	AI-driven models improve water conservation, infrastructure resilience, and smart city sustainability.
23	Cuaqi et al. (2021)	Global	Can Precise Irrigation Support the Sustainability of Protected Cultivation? A Life-Cycle Assessment and Life-Cycle Cost Analysis	Good	Observational	AI-assisted precise irrigation systems for sustainable, protected cultivation	N/A	N/A	N/A	N/A	N/A	AI-driven precise irrigation vs. conventional irrigation methods	AI-integrated irrigation improves water use efficiency, reduces environmental impact, and enhances economic sustainability in protected cultivation
24	Fang et al. (2021)	China	Spatiotemporal Variability of Drought and Its Multi-Scale Linkages with Climate Indices in the Huaihe River Basin, Central China, and East China	Good	Observational	AI-based spatiotemporal drought analysis using climate indices	N/A	N/A	N/A	N/A	N/A	AI-driven drought assessment vs. traditional hydrological modeling	AI-enhanced analysis improves understanding of regional drought variability and climate index linkages, supporting water resource planning
25	Gomes & Blanco (2021)	Brazil	Daily Rainfall Estimates Considering Seasonality from a MODWT-ANN Hybrid Model	Good	Experimental	MODWT-ANN hybrid model for rainfall estimation	N/A	N/A	N/A	N/A	N/A	MODWT-ANN hybrid model vs. conventional rainfall estimation methods	AI-based hybrid modeling improves rainfall prediction accuracy, supporting hydrological planning and water resource management
26	Magidi et al. (2021)	Africa (Mpumalanga Province)	Application of the Random Forest Classifier to Map Irrigated Areas Using Google Earth Engine	Good	Experimental	RF machine learning classifier applied to Landsat and Sentinel satellite imagery for	2018–2020 dataset of cultivated land	Irrigated areas classified using	N/A	Rainfed agriculture	N/A	RF-based irrigation classification vs. conventional land-use	AI-driven classification achieved 88% accuracy in mapping irrigated areas, supporting agricultural water management and food security assessments.
						irrigation mapping		NDVI analysis		areas		classification methods	
27	Xu et al. (2020)	China	Application of a Hybrid ARIMA–SVR Model Based on the SPI for the Forecast of Drought—A Case Study in Henan Province, China	Good	Experimental	Hybrid ARIMA-SVR model for drought forecasting	N/A	N/A	N/A	N/A	N/A	ARIMA-SVR model vs. traditional drought prediction models	AI-based hybrid modeling improves drought forecasting accuracy, enabling proactive water management strategies
28	Kocian & Incrocci (2020)	Global	Learning from Data to Optimize Control in Precision Farming	Good	Experimental	AI-driven data learning techniques for optimizing control systems in precision agriculture	N/A	N/A	N/A	N/A	N/A	AI-based precision agriculture control vs. conventional agricultural management	AI-enabled learning optimizes precision farming operations, improving water use efficiency and crop yield.
29	Mokhtari & Akhoond-Ali (2020)	Iran	Data Fusion and Machine Learning Algorithms for Drought Forecasting Using Satellite Data	Good	Experimental	ML and satellite data fusion for drought forecasting	N/A	N/A	N/A	N/A	N/A	AI-based satellite data-driven drought forecasting vs. traditional meteorological models	AI-driven fusion models improve drought prediction accuracy and enhance early warning systems.
30	Myoung et al. (2020)	South Korea	Long-Lead Predictions of Warm Season Drought in South Korea Using North Atlantic SST	Good	Experimental	AI-enhanced climate modeling integrating North Atlantic SST data for drought prediction	N/A	N/A	N/A	N/A	N/A	AI-enhanced SST-based drought prediction vs. conventional climate models	AI models improve long-term drought forecasting, aiding regional water resource management
31	Tian et al. (2020)	Global	Coupled Machine Learning and Unmanned Aerial Vehicle-Based Hyperspectral	Good	Experimental	ML integrated with UAV hyperspectral imaging for soil	N/A	N/A	N/A	N/A	N/A	AI-UAV-based soil moisture estimation vs. traditional	AI-UAV-based estimation improves soil moisture assessment accuracy,
			Data for Soil Moisture Content Estimation			moisture estimation						field measurement methods	supporting precision irrigation strategies.
32	Venkatasubramanian et al. (2020)	India	Designing Community-Based Intelligent Systems for Water Infrastructure Resilience	Good	Experimental	AI and community-based intelligence for enhancing water infrastructure resilience	N/A	N/A	N/A	N/A	N/A	AI-driven community water resilience strategies vs. conventional infrastructure resilience planning	AI-enabled community intelligence enhances water infrastructure monitoring, reducing failure risks and improving the sustainability of water systems.
33	Allawi et al. (2020)	Egypt	Developing Reservoir Evaporation Predictive Model for Successful Dam Management	Good	Experimental	Developed predictive modeling for reservoir evaporation estimation in dam management	N/A	N/A	N/A	N/A	N/A	AI-driven reservoir evaporation prediction vs. conventional hydrological models	AI-enhanced models improve evaporation forecasting, aiding in efficient water storage and dam operation.
34	Fung et al. (2020)	Malaysia	Improved SVR Machine Learning Models for Agricultural Drought Prediction at Downstream of Langat River Basin, Malaysia	Good	Experimental	SVR ML models for drought prediction	N/A	N/A	N/A	N/A	N/A	AI-based SVR drought forecasting vs. traditional meteorological prediction models	SVR models improve drought prediction accuracy, supporting sustainable agricultural water management
35	Herchuri et al. (2020)	North and West Africa	Spatio-Temporal Patterns of Drought and Impact on Vegetation in North and West Africa Based on Multi-Satellite Data	Good	Observational	AI and remote sensing analysis of drought impact on vegetation using multi-satellite data	N/A	N/A	N/A	N/A	N/A	AI-enhanced multi-satellite drought analysis vs. conventional drought impact assessments	AI-driven satellite analysis offers enhanced spatiotemporal drought monitoring, thereby improving early warning and mitigation strategies.
36	Li et al. (2019)	Global	Hydrological Drought Forecasting Incorporating	Good	Experimental	AI-based drought forecasting incorporating both climatic and	N/A	N/A	N/A	N/A	N/A	AI-based hybrid drought forecasting vs.	AI-enhanced models improve drought prediction by integrating climate
			Climatic and Human-Induced Indices			anthropogenic factors						traditional hydrological models	variability and human-induced influences
37	Sun & Scanlon (2019)	Global	How Can Big Data and Machine Learning Benefit Environment and Water Management: A Survey of Methods, Applications, and Future Directions	Good	Systematic Review	Review of AI, big data, and ML applications in environmental and water resource management	N/A	N/A	N/A	N/A	N/A	AI-based environmental monitoring vs. conventional management approaches	AI and big data enhance decision-making, improve water sustainability, and optimize resource allocation

Abbreviations: AI: Artificial Intelligence; ANN: Artificial Neural Network; ARIMA: Auto-Regressive Integrated Moving Average; BMA: Bayesian Model Averaging; BVAR: Bayesian Vector Autoregressive; BWO: Beluga Whale Optimization; BTOP: Bucket-type TOPography-based hydrological MODEL; CNN: Convolutional Neural Network; DL: Deep Learning; DO: Dissolved Oxygen; DSS: Decision Support System; GLDAS: Global Land Data Assimilation System; GIS: Geographic Information System; INLA: Integrated Nested Laplace Approximation; IoT: Internet of Things; LSTM: Long Short-Term Memory; ML: Machine Learning; MODIS: Moderate Resolution Imaging Spectroradiometer; MODWT: Maximal Overlap Discrete Wavelet Transform; MQTT: Message Queuing Telemetry Transport; MSI: Multi-Spectral Instrument; MSWI: Multivariate Standardized Lake Water Level Index; NDVI: Normalized Difference Vegetation Index; N: Number; OLI: Operational Land Imager; PID: Proportional-Integral-Derivative; RELM-SO: Regularized Extreme Learning Machine with Self-Optimization; ResNet: Residual Network; RF: Random Forest; RMSE: Root Mean Square Error; RNN: Recurrent Neural Network; RT-CLAD: Real-Time Chironomid Larva Detection;SPI: Standardized Precipitation Index; SST: Sea Surface Temperature; SVM: Support Vector Machine; SVR: Support Vector Regression; SWC: Soil-Water Content; TOT_N: Total number; TDS: Total Dissolved Solids; UAV: Unmanned Aerial Vehicle; U-Net-ConvLSTM: U-Net-Convolutional Long Short-Term Memory; W-ARIMA: Wavelet-ARIMA; WWTPs: Wastewater Treatment Plants; YOLO: You Only Look Once.

3.2. Urban Water Distribution and Leak Detection

AI is revolutionizing urban water distribution systems by optimizing efficiency, accuracy, and sustainability. Its predictive capabilities, automated monitoring, and anomaly detection help detect leaks early, ensuring better water conservation and operational efficiency. One of AI's most significant contributions to urban water distribution is predictive modeling. Traditional statistical methods often fail to capture the complexities of water demand fluctuations, infrastructure deterioration, and leakages. Sadiki and Jang demonstrate that

LSTM networks, a type of recurrent neural network (RNN), can accurately predict hydraulic parameters such as flow rate, pressure, turbidity, and chlorine levels that are still present in the water [2]. With an R^2 value of 0.86 for discharge and 0.97 for conductivity, the study confirms that AI models significantly enhance water distribution system monitoring, enabling real-time decision-making. Leak detection remains a major challenge in urban water management, leading to substantial water loss and financial costs. AI-driven models enhance real-time anomaly detection and system diagnostics. Joseph applied logic-based rules and ML techniques to analyze SCADA sensor data in a 450 mm pipeline in Australia [1]. With an F1 score of 0.69 and an ROC-AUC (Receiver Operating Characteristic – Area Under the Curve) of 0.72, the study found that the local outlier factor (LOF) algorithm outperformed other ML methods. This highlights AI's capacity to detect irregularities in flow, pressure, and pipe conditions, resulting in faster leak identification and reduced response times. Integrating AI with GIS has revolutionized urban water management. Panganiban et al. developed a GIS-based DSS for Cauayan City, Philippines, incorporating MIKE Operation software to optimize water distribution and stormwater harvesting [3]. The study reveals that AI-driven water management can significantly enhance the spatial planning, predictive maintenance, and resource allocation of urban water infrastructure, thereby reducing distribution losses and improving storage efficiency. AI plays a critical role in water consumption assessment, helping utilities anticipate demand patterns and reduce non-revenue water losses. Morain et al. systematically reviewed ML and hybrid AI models, finding that hybrid AI approaches outperform standalone models due to their adaptability to various urban water conditions [21]. Similarly, Badidi explores how edge AI and blockchain technologies enhance smart water distribution networks [23]. Edge AI and blockchain technologies improve water flow optimization, leak detection, and smart metering, transforming urban water infrastructure into self-regulating ecosystems and reducing dependence on cloud computing. Beyond prediction and detection, AI-driven automated control systems enhance operational efficiency. Joseph discusses how Intelligent Urban Water Networks (IWNs) integrate SCADA, AI, and IoT for real-time monitoring and predictive maintenance [24]. AI-based monitoring in Australia and India reduces water losses by up to 25% by automating pipeline management, pressure regulation, and infrastructure maintenance, ensuring long-term network resilience. AI enhances urban water management, but challenges persist, including the need for robust data requirements and the need for improved predictive accuracy. Further research is needed to optimize models for diverse environmental and seasonal conditions [1, 2]. AI's success in leak detection relies on sensor placement, data preprocessing, and computational power, which may be challenging for aging cities. Integrating AI techniques, real-time analytics, and cross-sector collaboration can create adaptive urban water systems, thereby improving water conservation, reducing costs, and enhancing service reliability. An important aspect of AI-driven water management is predicting reservoir evaporation, which is critical in dam and reservoir operations. Allawi et al. developed a modified Coactive Neuro-Fuzzy Inference System (CANFIS) to improve evaporation prediction. Their model achieved a coefficient of determination (R^2) of 0.96 for the Aswan High Dam and 0.91 for the Timah Tasoh Dam, outperforming traditional physical models [25]. The results demonstrated the effectiveness of their approach in accurately predicting evaporation rates for these dams. AI enhances decision-making for urban water infrastructure adaptation, integrating forecasting models with spatial planning and cross-sectoral optimization. This helps ensure resilience against population growth and climate uncertainties. A significant advancement in AI for water resource planning is Adaptive Intelligent Dynamic Water Resource Planning (AIDWRP), proposed by Xiang et al. [26]. The Markov Decision Process (MDP)-based model enhances water supply and demand management in urban settings by incorporating stochastic dynamics and hydraulic constraints, thereby improving economic efficiency and environmental sustainability. AI-driven digital water

innovations optimize water conservation, infrastructure sustainability, and efficiency, with the integration of data analytics, ML, and IoT transforming urban water networks, paving the way for future smart water grids [27]. AI technologies are revolutionizing water management, enhancing efficiency, cost savings, and sustainability in cities through leak detection, predictive modelling, and GIS-integrated decision-making tools.

3.3. Agriculture and Irrigation Systems

Agriculture faces numerous challenges, including climate change, water scarcity, and the need for increased food production. AI can optimize water management and crop productivity by integrating IoT technologies, DSS, and remote sensing data. Recent studies have demonstrated that integrating AI and IoT in smart irrigation systems enhances irrigation scheduling, reduces waste, and improves sustainability [4]. Zia et al. compared IoT-based and traditional irrigation scheduling in a subtropical lemon farm, where the AI-powered system reduced water usage by 46% while increasing yield by 35% [5]. Predicting crop water demand accurately is crucial for efficient irrigation. Ye et al. proposed a DL framework using the UNet-ConvLSTM model to integrate remote sensing data with AI for water demand forecasting [7]. Their model achieved high accuracy (R^2 = 0.927 on Moderate Resolution Imaging Spectroradiometer (MODIS) and 0.935 on GLDAS datasets), outperforming traditional forecasting methods. Similarly, Elshaikh et al. applied ML models, including artificial neural networks (ANNs) and support vector machines (SVMs), to predict soil moisture and irrigation needs, resulting in a reduction of up to 30% in water consumption [6]. AI enhances adaptive irrigation techniques by adjusting schedules in real-time based on weather conditions, improving water use efficiency, and reducing waste, particularly in water-scarce regions.AI-powered DSS analyzes real-time environmental data to provide irrigation recommendations. Mishra et al. implemented an Adafruit IO-based smart irrigation system, which reduces water wastage and maintains optimal soil conditions [28]. Nsoh et al. demonstrated that AI-enhanced DSS improves water use efficiency and crop resilience by tailoring schedules [29]. As DSS evolves, integration with AI-driven chatbots and automated advisory services is becoming more common. These systems enable farmers to receive personalized irrigation recommendations tailored to their soil conditions, climate data, and crop type, providing user-friendly insights that enhance agricultural decision-making. AI-integrated remote sensing provides large-scale insights into agricultural water use. Garofalo et al. utilized RF algorithms and satellite imagery to predict carob tree physiological responses to different irrigation levels, achieving high accuracy in monitoring water stress [30]. Magidi et al. applied the RF classifier in Google Earth Engine (GEE) to map irrigated areas in South Africa, identifying a 12.17% increase in irrigation over a one-year period [31]. AI-driven remote sensing optimizes regional water distribution, irrigation strategies, and early drought detection in crops, enabling timely interventions and efficient water management across large agricultural landscapes. Monitoring soil moisture levels is essential for efficient irrigation scheduling. Rahaman et al. proposed a privacy-centric AI framework for smart irrigation, securing sensor data while optimizing water usage [4]. Their AI system improved data accuracy and decision-making efficiency. Similarly, Kocian et al. used reinforcement learning algorithms in IoT-based soil monitoring systems, enhancing water conservation by reducing unnecessary irrigation cycles [32]. AI-powered automated irrigation enhances water conservation efforts. Canaj et al. analyzed precision irrigation systems for greenhouse zucchini production, demonstrating a 38.2% reduction in water use while maintaining yields [33]. Wong et al. applied AI-based evapotranspiration models in California's Central Valley, improving water allocation in drought-prone areas. These examples showcase how AI-driven automation revolutionizes agricultural water management [34]. AI-driven soil sensors are improving real-time monitoring, reducing manual testing, and continuously updating soil health parameters to ensure crop watering without excess irrigation. Sustainability is a key goal of AI-powered irrigation systems. Ferreira et al. examined water management in horticulture, integrating IoT and AI for real-time monitoring and predictive analytics, reducing water use by 30% without compromising yields [35]. Branquinho et al. explored AI-based irrigation in vineyards, highlighting how DSS optimizes water

distribution while maintaining soil health [36]. AI also enhances the efficiency of renewable energy-powered irrigation systems. Ramadan et al. investigated AI-enhanced solar-powered irrigation, demonstrating significant water savings and energy efficiency [37]. Alamanos explored hydro-economic models integrating AI for irrigation infrastructure planning, reducing costs while improving water quality. These studies highlight the synergy between AI and renewable energy in sustainable farming [38]. AI is being used in agriculture to optimize irrigation and fertilization scheduling, reducing energy consumption and greenhouse gas emissions. However, challenges such as expensive implementation, information confidentiality concerns, and technical complexities persist. Elzaki et al. highlighted the need for AI-based water management policies to improve agricultural resilience, and further research is needed to make AI-driven irrigation systems more accessible and cost-effective [39]. Advancements in AI and IoT continue to address water scarcity, irrigation efficiency, and crop productivity. Al Mashhadany et al. [40] developed an AI-powered cloud-based IoT system for real-time environmental monitoring, integrating fuzzy logic and Proportional Integral Derivative (PID) controllers for optimal water pump efficiency. Alex et al. introduced an AI-based smart irrigation system using deep neural networks for intelligent valve regulation, dynamically adapting irrigation schedules based on soil moisture and ambient temperature [41]. AI-powered autonomous irrigation robots are revolutionizing agriculture by improving efficiency, optimizing water use, and promoting sustainability. These robots use advanced sensors and AI-driven decision-making to apply water precisely, reducing over-irrigation and waste. However, challenges like cost, scalability, and information security need to be addressed for widespread adoption. Collaboration among farmers, policymakers, and researchers is crucial for developing scalable AI solutions that support long-term agricultural viability.

3.4. Drought Prediction and Weather Forecasting

Drought prediction and weather forecasting are crucial areas of research in climate science. Traditional models struggle to capture climate patterns, leading to the rise of AI methods. AI-driven approaches improve short-term forecasting and enable long-term climate trend analysis, thereby aiding in water resource management and disaster preparedness. Various AI models have been developed for drought prediction, including SVMs, RFs, Extreme Learning Machines (ELM), and LSTM networks. Up to 95% of the time, a study by Hameed et al. found that a mixed model using Regularized Extreme Learning Machines (RELM) and the Beluga Whale Optimization (BWO) algorithm could accurately predict droughts in the Great Lakes region [42]. Similarly, Fung et al. demonstrated that Fuzzy-SVR (F-SVR) and Boosted-SVR (BS-SVR) outperform traditional statistical models in predicting agricultural drought in Malaysia [43]. LSTM networks have demonstrated exceptional performance in long-term drought prediction, capturing nonlinear dependencies in climate data. Shah et al. achieved 99% accuracy in Pakistan, and Taylan et al. accurately predicted severe drought events in Northwest Türkiye [10, 11]. The combination of AI models with statistical methods enhances predictive performance. In Henan Province, China, Xu et al. developed a hybrid ARIMA-SVR model that was more effective at predicting multiscale SPI values than standalone ARIMA models [9]. Similarly, Rezaiy et al. integrated wavelet transform with ARIMA to improve Afghanistan's short- and long-term drought forecasts, reducing prediction errors by 30% [8]. Hydrological drought forecasting benefits from AI models incorporating lake water levels, streamflow data, and precipitation records. Hameed et al. examined DL LSTM and hybrid Regularized Extreme Learning Machine with Self-Optimization (RELM-SO) models to determine which could better predict the Multivariate Standardized Streamflow Index (MSSI) in Malaysia. They discovered that hybrid models were better at making predictions for more than one month [44]. Meanwhile, Li et al. showed that integrating climate indices (Niño-3.4,

AMO, PDO) with AI models enhances hydrological drought predictions in China's Luanhe River Basin [45]. AI-driven simulations and satellite-derived datasets enhance forecasting, improving drought monitoring in Iran. Mokhtari et al. used MODIS, TRMM, and SMOS data for accurate classification [46]. Gomes et al. demonstrated that a hybrid Maximal Overlap Discrete Wavelet Transform (MODWT)-ANN model outperforms standard ANN models in daily rainfall estimation, aiding drought prediction in Brazil [47]. AI models are increasingly used to predict groundwater droughts by analyzing past groundwater levels and meteorological conditions. Kang et al. employed an LSTM-based groundwater drought model in South Korea, integrating hydrometeorological data to predict groundwater depletion trends accurately [48]. Liu et al. employed an LSTM model to forecast groundwater quality indicators in China, highlighting the seasonal variations that affect water availability [49]. Furthermore, AI-driven remote sensing technologies are utilized to track groundwater movements across large geographic regions, enhancing predictions of water shortages and aiding in mitigating the impact of prolonged drought periods.

Beyond drought, AI has revolutionized weather forecasting by improving rainfall and temperature predictions. Myoung et al. developed an LSTM-based model for long-lead precipitation forecasting, showing that North Atlantic SST (Sea Surface Temperature) anomalies have a significant influence on South Korea's summer drought patterns [50]. Tian et al. applied hybrid AI models to predict soil moisture levels in Xinjiang, China, aiding regional climate modelling [51]. Filling gaps in missing precipitation data is essential for reliable weather forecasting. Qiu et al. developed an imputation method, Multiple Linear Regression (MLR), which combines BPNN, RF, and SVR models to fill in missing precipitation records in China [52]. This method achieved an NSE of 0.8329, ensuring high accuracy in hydrological modelling. AI models enable the development of real-time early warning systems for drought and extreme weather. Kim et al. developed the OneMap drought monitoring system by integrating Bayesian Principal Component Analysis (BPCA) with satellite and ground-based data. This system is very good at classifying droughts at multiple scales [53]. Park et al. designed a diagnostic drought prediction model using satellite-based vegetation indices, reducing forecast uncertainties in Kyrgyzstan [54]. AI models are being utilized in South Korea, China, and other countries to predict groundwater droughts by analyzing past levels and meteorological conditions. Recent advancements in AI have significantly improved drought prediction and weather forecasting accuracy. Bayesian Model Averaging (BMA) is gaining attention as an ensemble approach for improving AI-driven drought predictions. It was done by Achite et al., who combined several ANNs that were improved with various swarm intelligence methods, such as the Water Strider Algorithm (WSA), Particle Swarm Optimization (PSO), Salp Swarm Algorithm (SSA), and Sine Cosine Algorithm (SCA), to guess the SPI over a range of timescales [55]. Their study found that BMA improved forecast accuracy by 26–62% compared to standalone ANN models. Hydrological droughts, which affect water availability in rivers and reservoirs, necessitate predictive models that incorporate streamflow and precipitation data. To determine the Standardized Runoff Index (SRI) values in Algeria, Achite et al. employed a model that combined SVR with the Election Algorithm [56]. They also introduced an Adaptive Neuro-Fuzzy Inference System (ANFIS) optimized using the Water Cycle Algorithm (WCA), which outperforms traditional ANFIS models in forecasting hydrological droughts. AI models are being utilized in South Korea, China, and other countries to predict groundwater droughts by analyzing past levels and meteorological conditions.

3.5. Natural Water Distribution

AI integration in water distribution enhances hydrological modelling, improves drought monitoring, and facilitates more effective reservoir management, thereby increasing accuracy, optimizing resource allocation, and mitigating risks associated with climate variability. This ultimately benefits agriculture, urban planning, and ecological conservation. In particular, AI has substantially impacted drought variability and prediction. Fang et al. analyzed the spatiotemporal drought patterns in the Huaihe River Basin using wavelet analysis and ML techniques [57]. Their study linked large-scale climate phenomena, such as the

Arctic Oscillation and El Niño-Southern Oscillation (ENSO), to drought patterns, enabling improved drought forecasting. Henchiri also employed AI-driven remote sensing methods, including the Normalized Difference Vegetation Index (NDVI) and ML-based classification, to examine the effects of drought in North and West Africa [58]. Advancements in AI-driven drought forecasting have further improved risk management strategies. By integrating DL frameworks with historical climate data, researchers can now generate long-term drought predictions with increased accuracy. AI models that utilize convolutional neural networks (CNNs) and RNNs can analyze weather data to identify early signs of drought stress. This lets people save water and plan crops more efficiently. AI has also transformed runoff estimation by enhancing the accuracy of hydrological simulations. Humphries et al. employed ML techniques, including Decision Tree Forests (DTFs) and Multi-Layer Perceptron (MLP), to model runoff in the Mangla watershed [59]. Their results demonstrated that AI-based models significantly outperformed traditional approaches, with DTFs achieving the highest predictive accuracy. Xiao et al. further improved runoff modelling by combining time series models, such as ARIMA, LSTM, and a refined Prophet model, with the hydrological BTOP model (Bucket-type TOPography-based hydrological MODEL) [60]. The Prophet model, which incorporated domain-specific knowledge, improved Nash-Sutcliffe efficiency (NSE) by over 50%, demonstrating the power of AI in refining hydrological predictions. AI applications are transforming water quality assessment, with decision tree models achieving a 95.7% accuracy rate in predicting water suitability for irrigation in Telangana, India [61]. This helps optimize irrigation practices and prevent soil salinization, leading to more efficient water use in agriculture. AI is also being used to predict real-time water contamination events, alerting authorities to potential waterborne disease outbreaks or industrial spills. This predictive capability strengthens water safety management and supports policy development for better regulatory compliance in water quality monitoring. AI has significantly improved surface water resource monitoring and management, as demonstrated by Șerban et al. in Romania [62]. The study linked anthropogenic activities and climate-driven hydrological variations to lake shrinkage, emphasizing the need for AI-based continuous monitoring. AI-powered image recognition and satellite-based monitoring systems are also revolutionizing wetland conservation, providing detailed insights into habitat degradation, illegal water use, and the effects of climate change on aquatic ecosystems. These tools enable more effective policy implementation and resource allocation for environmental sustainability. Sheng et al. developed an AI-powered framework for dam safety management in China, incorporating big data analytics, ML, and IoT-based real-time monitoring [63]. The system provided early warnings, predictive maintenance insights, and automated decision support, reducing dam failure risks. AI's role in enhancing water infrastructure resilience and disaster prevention is also evident in hydroelectric power generation, where AI models optimize water storage and release schedules, ensuring sustainability and meeting growing energy demands in an environmentally responsible manner. AI applications for water distribution face challenges such as data scarcity, model generalizability, and computational constraints. High-quality datasets may not be readily available in remote regions, and regional variations in climate and geography can impact model generalizability. To address these issues, adaptive AI models should integrate diverse data sources and learn from new observations. Hybrid AI models, which combine ML with physical hydrological models and AI-driven DDSs, can enhance real-time monitoring and promote sustainable water governance.

3.6. Desalination, Water Treatment, and Quality Monitoring

The growing global demand for clean water has prompted research into efficient methods for water desalination, treatment, and quality monitoring. Traditional methods often struggle with complex and dynamic systems. AI and ML have emerged as transformative technologies, improving desalination efficiency, reducing

operational costs, and enhancing decision-making. Desalination, a crucial process for obtaining fresh water, is energy-intensive and requires precise control. Li et al. demonstrated that AI-driven dissolved oxygen control strategies enhance aeration in desalination processes, utilizing less energy while maintaining the optimal level of microbial activity [13]. Similarly, Makropoulos et al. introduced reinforcement learning-based smart planning agents to optimize decentralized water treatment systems, including desalination plants, enabling adaptive control strategies that adjust to varying environmental conditions and infrastructure constraints [64].

ML models have been extensively applied to forecast and improve the performance of desalination systems. Epasto et al. applied DL models, such as Prophet and RNNs, to forecast groundwater levels, which is crucial for desalination plant operation [12]. Research on AI and ML is revolutionizing water management by improving desalination efficiency, reducing operational costs, and enhancing decision-making in complex, dynamic systems.

AI-driven filtration processes, including membrane technology and adsorption methods, have been enhanced through the use of predictive modelling. Jang et al. created Real-Time Chironomid Larva Detection (RT-CLAD), an AI-based real-time monitoring system, to find chironomid larvae in drinking water. This demonstrates how DL models, such as CNN and You Only Look Once (YOLO), can be utilized to automate water safety inspections [65]. AI-driven automation in water treatment plants optimizes chemical dosing, filtration, and aeration. Rajitha et al. reported that AI-powered control systems reduce operational costs by adjusting real-time treatment parameters based on water quality sensor data [66]. AI models, such as neural networks and decision trees, enable continuous optimization, minimizing human intervention while maintaining treatment efficiency. Advanced AI-based feedback loops can fine-tune treatment plant operations, reducing the risk of chemical overdosing or under-dosing, thereby improving cost-effectiveness and sustainability. AI enhances water quality monitoring by leveraging real-time sensor data and remote sensing technologies. Olentsova et al. employed ML models, including RF and linear regression, to predict post-monsoon groundwater quality in India [14]. These models successfully forecast variations in TDSs and pH, providing valuable insights for water managers to prevent contamination events. Satellite-based AI models have revolutionized large-scale water quality monitoring. Schaeffer et al. developed a Bayesian spatiotemporal model using Sentinel-3 satellite data to predict harmful cyanobacterial blooms in U.S. lakes [15]. The model achieved 90% accuracy in forecasting WHO alert-level water quality exceedances, demonstrating AI's ability to efficiently monitor large water bodies and identify pollution sources. AI also plays a role in managing stormwater and preventing water contamination. Ramovha et al. applied AI-enhanced stormwater modelling tools, such as the Storm Water Management Model (SWMM) and Personal Computer SWMM (PCSWMM), to optimize flood control and pollution mitigation strategies [67]. AI-driven DSSs utilize rainfall, land use, and pollution data to develop adaptive stormwater treatment solutions, improve emergency response planning, and reduce risk in urban water management. Ensuring the resilience of water infrastructure is a growing concern, particularly in light of climate change. Venkatasubramanian et al. developed AquaSCALE, a cyber-physical system that integrates AI, IoT, and geospatial analytics to enhance the resilience of water distribution networks [68]. Their system optimizes sensor placement, predicts failures, and improves disaster response capabilities, demonstrating AI's role in maintaining robust water infrastructure.

AI-powered water management systems optimize resource utilization by integrating sensor networks, IoT devices, and predictive analytics. This enables us to see how water is being distributed and used in irrigation and city supply networks in real time [69]. AI-powered water management systems optimize resource utilization by integrating sensor networks, IoT devices, and predictive analytics. This enables us to monitor the real-time distribution and use of water in irrigation and city supply networks. Epasto et al. highlighted how AI-powered forecasting tools assist in setting regulations for sustainable groundwater management [12]. The evolving role of AI in water management involves expanding real-time adaptive control, enhancing the accuracy of AI models, and

integrating AI with smart city initiatives. According to Venkatasubramanian et al., AI-driven cross-sector partnerships, such as the Smart Water and Digital Economy (SWADE) initiative, would facilitate the sharing of data among networks that handle potable water, wastewater, and stormwater, thereby improving overall water security [68]. AI is transforming water management by optimizing energy use, automating assessments, and enhancing the resilience of infrastructure. However, data integration challenges persist. Future research should aim to improve model transparency, ensure equitable access, and enhance the integration of multi-source data. AI, IoT, blockchain, and digital twins will contribute to smarter, more resilient water infrastructure globally.

3.7. Future Directions and Challenges

AI is revolutionizing global challenges such as agriculture, energy management, and urban development. However, challenges like infrastructural deficiencies, financial constraints, cybersecurity risks, and trust issues hinder its full potential. The role of AI in agriculture is expanding, with applications in crop production, irrigation, disease detection, and supply chain management. Ahmad et al. emphasize that AI-driven DSSs, predictive analytics, and remote sensing technologies enhance yield forecasting and land monitoring [70]. AI-powered plant disease identification is a promising technology; however, challenges such as financial constraints, technical expertise, and infrastructure need to be addressed through effective policies and interdisciplinary collaboration. AI is also advancing precision agriculture by improving soil analysis and irrigation efficiency. Awais et al. discuss how AI-driven models, such as RFs and SVMs, enhance soil texture assessments, enabling real-time decision-making for sustainable farming [71]. AI-integrated fiber optic sensors enhance soil-water content measurement, supporting the development of smart irrigation systems. However, standardization, interpretability, and implementation costs remain barriers, requiring further research for widespread adoption. Energy management is another critical area where AI is revolutionizing efficiency and sustainability. Aldarraji et al. highlight the potential of AI-based forecasting models in optimizing electricity supply and demand, particularly in Iraq's energy sector [72]. AI models, such as ML and DL, are effective in forecasting and time-series analysis; however, challenges like data scarcity, digital infrastructure limitations, and policy constraints need to be addressed. Smart cities rely heavily on AI for urban sustainability, governance, and public services. AI applications include energy management, transportation, healthcare, and waste management [73]. However, challenges like information security, cybersecurity threats, and infrastructure limitations persist. Addressing these requires robust regulatory frameworks, investment in AI infrastructure, and public awareness campaigns to build trust in AI solutions. In smart water management, AI plays a crucial role in enhancing resource allocation and sustainability. Bouramdane et al. explore the use of multi-criteria decision-making (MCDM) methods, such as the Analytical Hierarchy Process (AHP), to prioritize water conservation strategies [74]. AI-driven smart metering improves urban water efficiency, while rainwater harvesting and greywater recycling improve sustainability. Challenges include high implementation costs and community engagement. Integrating AI with circular economy principles and Industry 4.0 technologies can drive sustainability in the water industry. Silva et al. emphasize that AI-powered big data analytics and IoT solutions facilitate real-time water quality monitoring and predictive maintenance [19]. Decentralized wastewater treatment and rainwater harvesting systems enhance sustainability; however, fragmented policies and regulatory barriers hinder their large-scale adoption. Strategies should focus on financial incentives, public-private partnerships, and policy integration to achieve effective outcomes. Climate change is another major challenge, and AI plays a pivotal role in adaptation and mitigation. Sun et al. discuss AI-driven solutions in viticulture, where rising temperatures and water scarcity pose threats to grapevine growth and wine production [75]. AI-powered irrigation techniques and soil amendments, such as biochar, enhance water use and climate

resilience, but significant investments and long-term planning are necessary for effective integration. AI is also proving invaluable in water security and resilience, particularly in drought-prone regions. Anandan et al. demonstrate how IoT and SVM classifiers enable real-time drought prediction [76]. AI-driven predictive analytics can help manage water resources, ensure sustainability, and mitigate agricultural losses; however, regional adoption variability and infrastructure limitations may hinder their full implementation in underdeveloped areas. Wang et al. highlight China's challenges in adopting AI and IoT, including infrastructural deficiencies, financial constraints, cybersecurity risks, and a lack of trust [77]. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method highlights that insufficient infrastructure and funding are primary barriers, while cybersecurity concerns and public scepticism further slow adoption. The study highlights the importance of strategic investments, effective regulatory policies, and active public engagement in promoting AI adoption in smart cities.

Table 2. AI technologies and models used in different domains of water management.

AI Technology	Urban Water Distribution	Smart Irrigation	Drought Prediction	Desalination & Wastewater	Water Quality Monitoring	Challenges & Scalability
IoT Sensors	✓	✓		✓	✓	✓
ML	✓	✓	✓	✓	✓	✓
DL	✓	✓	✓	✓	✓	✓
GIS-Based Monitoring	✓	✓	✓			
Remote Sensing		✓	✓		✓	
AI-Based Leak Detection	✓					
Smart Water Meters	✓					
Blockchain for Water Transactions	✓	✓			✓	✓
AI-Driven Weather Models			✓			
Big Data Analytics	✓	✓	✓	✓	✓	✓

Abbreviations: AI: Artificial Intelligence; DL: Deep Learning; GIS: Geographic Information System; IoT: Internet of Things; ML: Machine Learning. Kannan et al. highlight the importance of ethical considerations in AI deployment for environmental sustainability, emphasizing transparency, privacy, and equity [16]. They argue that responsible AI governance is crucial to mitigate unintended consequences, ensuring that AI-driven sustainability efforts align with global equity and ethical standards. Responsible AI governance is essential for mitigating unintended consequences and maintaining trust.

Limitations

This review is subject to certain limitations:

- The study only included articles from four databases, potentially excluding relevant studies published elsewhere.
- The review focused on studies published in English, omitting non-English research that may provide valuable insights.
- Some AI applications in water management are still in the early stages of research or pilot projects, limiting the availability of data for large-scale implementation.

Despite these limitations, this systematic review provides a comprehensive overview of the current state of AI in water management, highlighting advancements, challenges, and future research directions.

AI can revolutionize agriculture, energy management, water management, and the development of smart cities. However, significant challenges must be overcome to ensure its seamless integration and widespread adoption. Despite these challenges, the future of AI remains promising. Addressing infrastructural limitations through improved digital infrastructure and connectivity can facilitate the implementation of AI across various sectors. Enhancing cybersecurity measures and transparency in AI governance can improve trust and adoption rates. Furthermore, interdisciplinary collaborations between policymakers, researchers, and industry leaders are crucial in developing AI-driven solutions that align with societal needs and sustainability goals. While this review provides a comprehensive overview, it is limited by its reliance on English-language publications from four databases and by the scarcity of large-scale empirical data for some early-stage AI applications. Further research should be conducted to refine AI models, address regulatory and ethical concerns, and promote global collaboration. By overcoming these barriers, AI can drive sustainable development, enhance urban resilience, and create a smarter, more efficient world. With the increasing integration of AI across multiple sectors, it is vital to establish responsible AI governance, promote international cooperation, and invest in infrastructure that supports AI

innovation for long-term environmental and societal benefits.

Conflict of Interest

The authors declare that they have no conflict of interest.

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