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Practice and Prospects of Smart Water Management Construction in the Context of Digital Transformation

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ABSTRACT

Driven by urban expansion and rapid population growth, water management is transitioning from traditional models towards digitally-enabled smart water systems. This paper examines smart water management practices within the context of digital transformation. It specifically discusses four key areas of implementation: (1) comprehensive monitoring via IoT sensing, (2) water dispatch using digital twins, (3) intelligent emergency response for drainage, and (4) block-level collaborative water management. Furthermore, the paper prospectively analyzes future trends in smart water development, aiming to facilitate the digital transformation of the water industry.

INTRODUCTION

The convergence of water scarcity, deteriorating water quality, and aging urban infrastructure has exposed systemic deficiencies in conventional water management practices. These include delayed information acquisition, inefficient dispatch responses, and inadequate decision-making frameworks [1]. As emphasized in “The 14th Five-Year Plan for Urban Wastewater Treatment and Resource Utilization” issued by China's Ministry of Housing and Urban-Rural Development (MOHURD), advancing smart water management systems is critical for enhancing water governance capabilities, requiring accelerated deployment of integrated intelligent perception and dispatch platforms. Furthermore, “The Overall Plan for Digital China Construction” (State Council, 2022) explicitly mandates the development of smart water conservancy and smart water management systems to deepen the integration of digital technologies with urban governance.

Confronted with increasingly complex urban water environments, the water sector urgently requires digital and intelligent transformation. This shift aims to establish an integrated closed-loop control system encompassing "perception-transmission-processing-application" workflows [2]. Against this backdrop of digital transformation, this study investigates practical implementations of smart water management and explores future developmental trajectories, providing both theoretical foundations and practical references for industrial digital upgrading.

OVERVIEW OF SMART WATER MANAGEMENT

Smart water management leverages technologies including the Internet of Things (IoT), cloud computing, big data, and artificial intelligence to establish an efficient, precise, and intelligent water resource manage-

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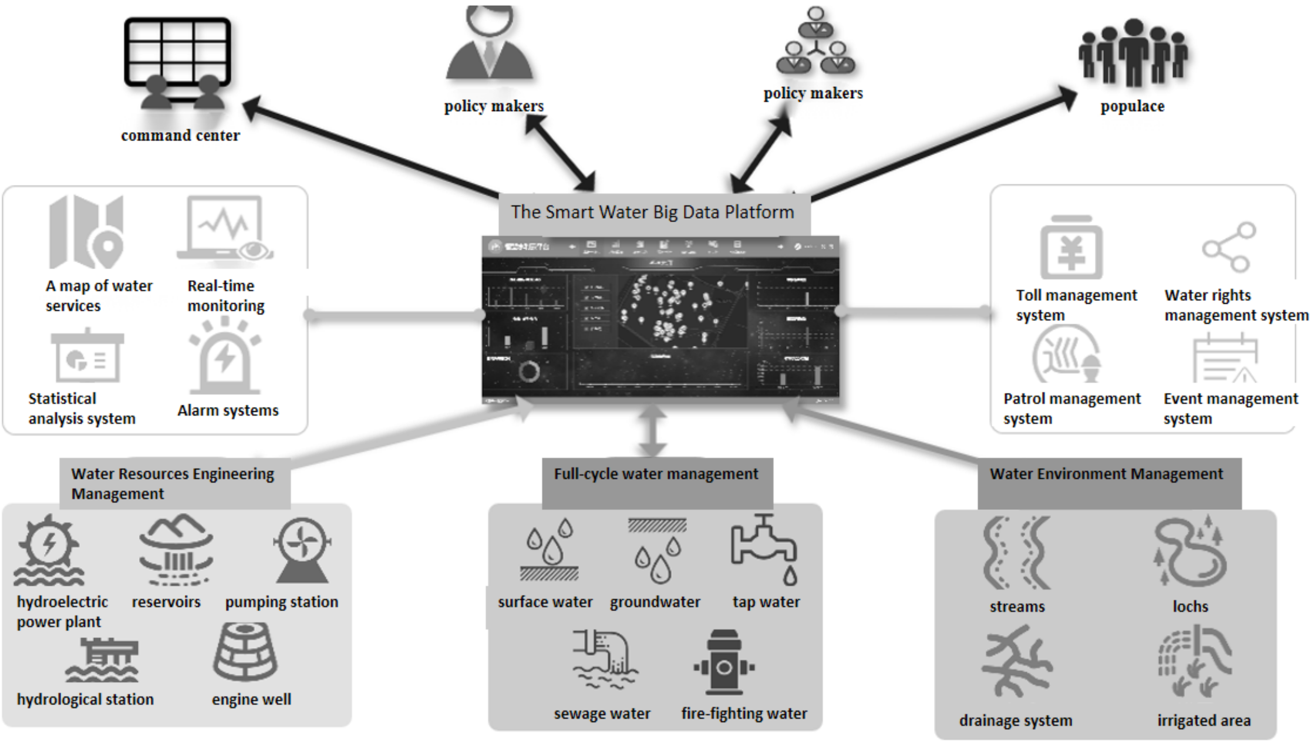

Figure 1 I Architecture of water resources utilization platform based on IoT technology

ment framework. This system encompasses monitoring, scheduling, governance, and service delivery.

The evolution of smart water management has progressed through four developmental phases: foundational, automated, informational, and intelligent, with continuous technological advancements [3]. Key milestones include:

Pre-1990: Reliance on manual monitoring and experience-based scheduling;

1990-1999: Gradual adoption of automated monitoring and remote control systems;

2000-2009: Maturation of data acquisition and analysis technologies, improving water resource utilization rates by 10-15%;

2010-Present: Deep integration of AI and digital twin technologies. For instance, Shenyang Water Group deployed 470,000 smart meters achieving a 95% automated billing and sales processing rate.

The smart water management market is expanding rapidly, with projections indicating a growth to RMB 37 billion by 2026. Future development will focus on enhancing data integration, intelligent governance, and precision control mechanisms to establish more efficient water resource management systems.

SMART WATER MANAGEMENT PRACTICES IN THE DIGITAL TRANSFORMATION CONTEXT

Comprehensive IoT Sensing and Monitoring

As the front-end core of operational state collection in smart water management systems, the perception layer undertakes dynamic monitoring of water bodies, hydraulic structures, and drainage systems. As illustrated in Figure 1, the smart water big data platform integrates perception, data processing, and service modules, establishing a closed-loop workflow of monitoring → diagnosis → regulation. This framework supports coordinated decision-making among dispatch centers, management personnel, and maintenance teams.

A representative implementation is Shenzhen's Longgang Smart Drainage System, which deploys over 3,800 intelligent sensing units across regional trunk pipelines and pumping stations. These units monitor 15 critical parameters including flow rate, liquid level, water quality, and gas concentrations. The system employs high-frequency ultrasonic level meters, electromagnetic flow meters, and LoRa smart water meters for data acquisition. A hybrid NB-IoT/5G transmission network ensures backhaul delays under 1 second with a 97% remote connectivity rate [4].

The anomaly detection module incorporates gradient variation modeling and transient recognition mechanisms, enabling automatic identification of water quality abnormalities, flow surges, and equipment vibration anomalies. This triggers real-time alerts to dispatch centers, achieving second-level response. Post-deployment results demonstrate:

- Annual early warnings identified: 231 cases
- Average response time reduction: 41.2%
- Enhanced operational precision through 3D visualization, trend analysis, and risk heat mapping

Partial monitoring data is publicly accessible through visualized interfaces, strengthening social oversight and public engagement.

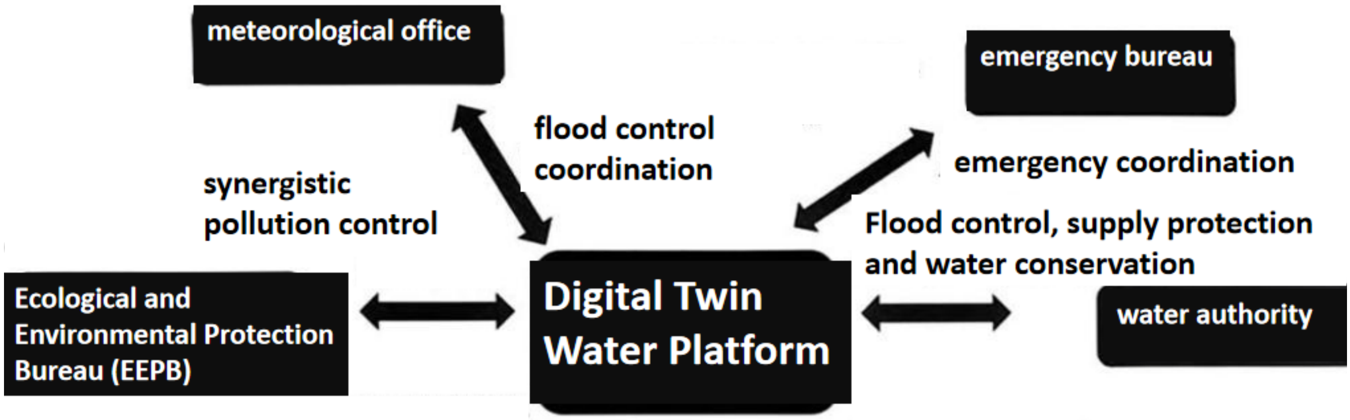

Figure 2 | Digital twin water scheduling collaboration architecture

Digital Twin-Enabled Water Scheduling

Digital twin water systems create real-time mappings between physical infrastructure and virtual environments, enabling simulation, evaluation, and predictive analysis of water management operations. As depicted in **Figure 2**, these platforms integrate multi-agency data sources (e.g., Meteorological Bureau, Ecology and Environment Bureau, Water Authority, and Emergency Management Bureau) to establish cross-departmental coordination mechanisms.

A representative implementation is Ningbo's "Yongshuitong" system, which consolidates urban hydrological parameters, water quality metrics, supply/drainage status, and rainfall data within a unified digital twin framework. The system architecture features:

- Perception Layer: Ultrasonic level gauges, radar flowmeters, and online water quality analyzers
- Network Layer: 5G+VPN dual-channel transmission achieving second-level data synchronization
- Data Layer: Real-time monitoring of 200+ pumping stations and pipeline nodes enabling BIM-hydraulic model co-simulation

An AI-powered multi-scenario scheduling engine autonomously generates flood control, water conservation, and emergency drainage strategies while dynamically regulating pump operations and gate positions. During the 2023 Meiyu flood season, the system predicted a 43-minute advance in southern river network water level rise, triggering preemptive drainage that prevented two road inundation events. Operational data indicates:

- Average scheduling response time: <8 minutes
- Gate-pump coordination rate: 93% [5]

The integrated data pathway shown in **Figure 2** demonstrates a closed-loop workflow from data acquisition to strategy execution, facilitating the transition from reactive response to proactive prediction and intelligent control in water management systems.

Intelligent Drainage Emergency Response

To address frequent extreme weather events and chronic flooding in low-lying urban areas, intelligent drainage emergency systems integrate sensing terminals, high-precision data links, and AI scheduling algorithms to establish dynamic response mechanisms. The system architecture typically includes:

- Liquid-level radar sensors
- Manhole cover displacement monitors
- Rainfall distribution sensors

Video surveillance terminals deployed at critical locations such as road junctions, pipeline confluences, and river outfalls [6].

A case implementation is Guangzhou's Yuexiu District "Smart Drainage Map" system, which integrates 487 monitoring points and 12 pumping stations. Utilizing LoRa-fiber-optic hybrid networks, it achieves 5-second real-time data updates. The platform incorporates an emergency simulation system combining DEM terrain modeling with hydraulic network analysis, enabling preemptive calculation of waterlogging indices and drainage capacity based on hourly rainfall forecasts.

During a July 2022 torrential rain event, the system predicted water level exceedance at two Beijing Road South nodes 12 minutes prior to critical thresholds. The dispatch platform immediately initiated preemptive pumping, discharging 9,600 m^3 of water and preventing traffic disruption. The system coordinates remote-controlled sluice gates, portable pumps, and visual command terminals for multi-zone hierarchical response.

Operational data demonstrates:

- 91.6% early warning accuracy (2021-2023)
- 7.4-minute average response time
- Enhanced urban drainage resilience and emergency capacity

Blockchain-Enabled Collaborative Water Management

Water management frequently involves cross-institutional data exchange, where traditional architectures face bottlenecks including ambiguous permissions and data silos. Blockchain-based collaborative systems overcome these limitations through distributed ledgers and smart contracts, enabling secure data sharing and controlled permission flows.

Nanjing's Jiangbei New Area Smart Water Platform exemplifies this approach, integrating operational systems from water supply, drainage, and reclamation plants. The platform consolidates 62 real-time parameters spanning water quality, pressure, and energy consumption metrics. Key features include:

- Consortium blockchain architecture granting role-based data access to seven stakeholder categories (e.g., Ecology and Environment Bureau, Water Authority, operators)
- Privacy-preserving computation encrypting sensitive data exclusively for authorized modeling systems
- Unified API/Smart contract interfaces connecting to Nanjing's City Information Modeling (CIM) platform for cross-departmental integration (urban development, meteorology, municipal administration)

During a 2023 energy consumption anomaly at a reclamation plant, blockchain audit logs enabled precise tracing to abnormal water quality regulation data, triggering maintenance response 5 hours earlier than conventional methods [7]. Operational results after 18 months demonstrate:

- 62% reduction in water quality alert transmission latency
- 3.4-fold increase in shared data access requests
- Transformation from demand-driven access to rule-based coordination

This framework establishes an actionable paradigm for regional data linkage and collaborative decision-making in water governance.

FUTURE PROSPECTS OF SMART WATER MANAGEMENT

Management Paradigm Shift for Enhanced Operational Efficiency

Future smart water systems will transition from "process scheduling" to "strategy evolution," necessitating self-learning operational frameworks. By incorporating reinforcement learning and graph neural networks, these systems can model dynamic feedback mechanisms using:

- Real-time plant operational data
- User consumption patterns
- Load fluctuation profiles

to enable adaptive control of pipeline networks, pumping stations, and pressurization systems.

The Beijing Shunyi Smart Pumping Station exemplifies this approach. Its self-optimization module - deploying time-series forecasting and iterative control algorithms - proactively adjusts pump switching logic during peak temperatures, reducing equipment load rates by 18%. Concurrently, edge computing nodes with autonomous anomaly recognition capabilities enhance localized fault recovery within distributed architectures.

This evolution eliminates central decision-making dependencies, instead establishing system-driven hierarchical coordination that enables genuine operational strategy intelligence.

Integrated Data Fusion for Collaborative Ecosystems

Smart water management systems are expanding their boundaries to interconnect with urban multidimensional systems, enabling deep data exchange and model coupling across transportation, meteorology, power, and emergency response domains.

The Ningbo Digital Twin Water Platform exemplifies this integration:

- Cross-platform interoperability with the City Information Modeling (CIM) platform, utilizing real-time road network and rainfall data to predict flood propagation paths and optimize scheduling prioritization
- Multi-source spatial analysis correlating urban heatmaps, sewage loads, and electricity consumption peaks to inform pipe network regulation strategies
- Semantic recognition middleware and permissioned APIs establishing bidirectional data bridges with municipal management and environmental protection agencies for coordinated cross-domain incident resolution

This evolution shifts governance models from prescriptive response to predictive model-driven frameworks, embedding urban water systems within citywide intelligence architectures to form dynamically self-regulating ecosystems.

Service Boundary Expansion and Security Reinforcement

Future water management systems will evolve into service-oriented platforms adopting Water-as-a-Service (WaaS) operational frameworks. These support on-demand subscription services including:

- Regional water usage simulation
- Energy consumption metering
- Remote regulation modules

Exemplified by Xiongan New Area's Sensing Water Cloud Platform, district-level distributed scheduling enables enterprise users to autonomously access pipeline network parameters and water conservation strategies, achieving self-service multi-tenant functionality.

Concurrently, security paradigms are shifting from perimeter encryption to end-to-end resilience through:

- Quantum key distribution for secure data transmission
- AI-driven risk identification models
- Zero-trust architecture implementations dynamically authenticating command sources and behavioral patterns to prevent concurrent internal privilege escalation and external intrusions

- The co-evolution of business models and security frameworks establishes twin pillars for stable operation and scalable advancement in the water sector.

CONCLUSION

Smart water management leverages digital transformation to achieve a paradigm shift from traditional approaches to intelligent, data-driven operations. Technologies including IoT, digital twins, artificial intelligence, and blockchain profoundly empower water systems, enabling:

- Enhanced monitoring precision
- Optimized scheduling efficiency
- Intelligent governance capabilities
- Streamlined cross-sectoral coordination

Confronting global water challenges, continuous technological innovation will strategically guide industry advancement, establishing secure, resilient, and sustainable water resource management frameworks.

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