Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Innovative Models for Construction and Pipeline Operation and Maintenance of Water Plants Driven by Smart Water Management

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Abstract: This article elaborates on the application of smart water management in the construction of water plants and the operation and maintenance of pipeline networks, covering all layers of the technical framework, including IoT perception. It introduces full chain application scenarios, such as water source monitoring. It also involves BIM, intelligent IoT device applications, breakthroughs in pipeline monitoring system construction and operation technology, as well as the economic cost-effectiveness of innovative models, evaluation index systems, system iteration and upgrading strategies, and points out limitations and future development directions.

Keywords: Smart water management; Construction and operation and maintenance; Technical framework

Online publication: October 10, 2025

1. Introduction

With the continuous development of technology, smart water management has become an important direction for the water industry. The *14th Five-Year Plan for Building a Water Saving Society*, released in 2021, emphasizes the importance of efficient utilization of water resources and intelligent upgrading of water management systems, providing policy support for the development of smart water management. Smart water management covers the entire chain of application scenarios from water source monitoring to intelligent regulation of pipeline networks. Its technical framework includes multiple layers, such as the Internet of Things perception layer, 5G communication layer, cloud computing platform layer, AI algorithm layer, etc. The data center and digital twin technology play a key role. At the same time, BIM technology, intelligent IoT devices, and other technologies have important applications in intelligent construction management, laying the foundation for innovative models of water plant construction and pipeline operation and maintenance, and are of great significance for improving water supply quality and efficiency.

2. Smart water technology system and core features

2.1. Smart water technology framework

The smart water technology framework covers multiple levels. The IoT perception layer collects water data, such as water quality and quantity, through sensors and other devices [1]. The 5G communication layer ensures high-speed and stable data transmission, enabling the timely transmission of massive water data. The cloud computing platform layer provides powerful computing capabilities for storing and processing data. The AI algorithm layer utilizes intelligent algorithms to analyze and mine data. Among them, the data center plays a key role in integrating data by aggregating and standardizing data from different sources, providing a foundation for subsequent analysis and application. The digital twin technology constructs a virtual model of the water management system to achieve real-time mapping and simulation of the real water management system, which helps optimize the operation and management of the water management system, and improve the efficiency and quality of water plant construction and pipeline operation and maintenance.

2.2. Typical application scenarios of intelligence

Smart water management covers the entire chain of application scenarios from water source monitoring to intelligent control of pipeline networks. In terms of water source monitoring, sensors and other technologies are used to obtain real-time data on water quality and quantity, providing a basis for subsequent processing. The automation of water plants enables intelligent control of the production process, improving efficiency and water quality stability. Intelligent regulation of pipeline networks can optimize water supply scheduling based on real-time data, reducing energy consumption [2]. In terms of construction supervision, real-time monitoring of the construction process is carried out through intelligent devices and systems to ensure construction quality and safety. The operation and maintenance warning function can detect potential faults in the pipeline network in advance, take timely measures, reduce losses, and ensure the continuity and reliability of the water supply.

3. Innovative practice of intelligent construction management

3.1. BIM technology integration for construction supervision

BIM technology plays an important role in intelligent construction management. In terms of factory planning, BIM models can be used for 3D visualization, making the design scheme more intuitive and easier for construction personnel to understand and execute [3]. For pipeline collision detection, BIM technology can simulate the pipeline laying situation in advance, accurately identify possible collision points, and effectively avoid rework and resource waste during the construction process. By combining BIM with relevant digital technologies in construction progress monitoring, real-time project progress information can be obtained, and deviations can be detected and adjusted in a timely manner by comparing the planned progress. In terms of quality monitoring, BIM models can record in detail various parameters and quality acceptance situations during the construction process, providing a basis for quality traceability and problem investigation, ensuring that construction quality meets standards.

3.2. Innovation in the application of intelligent IoT devices

Intelligent IoT devices have important innovative applications in intelligent construction management. In terms of monitoring deep foundation pits, intelligent sensing devices such as displacement sensors and water level sensors installed on the side walls of the pit can obtain real-time key data like pit deformation and groundwater level, and transmit the data to the monitoring center [4]. For pipeline welding quality inspection, intelligent testing equipment can be used to accurately determine the quality of the welding area through non-destructive testing techniques such as ultrasonic testing, radiographic testing, etc., and provide real-time feedback on the results. Meanwhile, it is crucial to establish a mechanism for device data collection and early warning response. The collected data needs to be analyzed in real-time. When the data exceeds the set threshold, the system will automatically issue a warning, and relevant personnel can take timely measures to ensure construction safety and quality.

4. Breakthrough in intelligent operation and maintenance technology for pipeline networks

4.1. Construction of a real-time monitoring system for the pipeline network

4.1.1. Layout of multi-source perception network

Under the drive of smart water management, it is crucial to build a multi-source perception network layout for real-time monitoring of pipeline networks. A three-dimensional layout plan that includes pressure, flow, and noise sensors should be designed. By properly arranging these sensors, key data on the operation of the pipeline network can be comprehensively obtained. For example, pressure sensors can monitor changes in pipeline pressure, flow sensors can measure water flow conditions, and noise sensors can help detect potential anomalies. At the same time, it is necessary to establish installation standards for online water quality monitoring terminals to ensure their accurate monitoring of water quality conditions. Through such a multi-source perception network layout, comprehensive and accurate data support can be provided for intelligent operation and maintenance of the pipeline network, achieving real-time and accurate monitoring of the operation status of the pipeline network, laying the foundation for innovative models of water plant construction and pipeline operation and maintenance [5].

4.1.2. Data transmission and cleaning mechanism

In the breakthrough of intelligent operation and maintenance technology for pipeline networks, the construction of a real-time monitoring system for pipeline networks is crucial. Real-time collection of key parameters of the pipeline network, such as pressure, flow rate, water quality, etc., is done through various sensors [6]. The data transmission and cleaning mechanism is the key to ensuring the effectiveness of monitoring data. Utilizing advanced communication technologies, such as building a hybrid network solution of NB IoT and LoRa, can achieve efficient and stable data transmission. For the collected data, due to possible issues such as noise and outliers, it is necessary to develop an anomaly recognition algorithm based on time series for cleaning. This algorithm can accurately identify data points that do not conform to normal patterns, improve data quality, and provide reliable data support for subsequent pipeline status analysis and operation decisions.

4.2. Intelligent diagnosis technology for pipeline leakage

4.2.1. Hydraulic model and AI fusion diagnosis

Combining the EPANET hydraulic model with an LSTM neural network to establish an intelligent diagnosis system for pipeline pressure anomalies can effectively improve the efficiency of pipeline operation and maintenance. The EPANET hydraulic model can accurately simulate the water flow state and pressure distribution in the pipeline network [7]. LSTM neural networks have the advantage of processing time series data and can learn and analyze pipeline pressure data. By integrating the two, the system can utilize the physical laws provided by hydraulic models and the learning ability of LSTM neural networks to diagnose pressure anomalies more accurately. This system can monitor the pressure of the pipeline network in real time, detect potential leakage points or other faults in a timely manner, provide strong support for the intelligent operation and maintenance of the pipeline network, and reduce the waste of water resources and economic losses.

4.2.2. Acoustic detection and positioning system

Develop a leakage voiceprint recognition algorithm based on convolutional neural networks, which can accurately identify different types and degrees of leakage voiceprint features through learning and analysis of a large number of leakage sound samples [8]. At the same time, by integrating GIS systems and utilizing their powerful geographic information processing capabilities, leak locations can be combined with geographic spatial information. The leakage voiceprint information identified through algorithms is accurately matched and located in GIS systems, thereby achieving fast and accurate determination of the location of pipeline leaks. This integrated system not only improves the accuracy of leak diagnosis but also provides accurate location information for subsequent repair and maintenance work, greatly improving the efficiency and quality of pipeline operation and maintenance.

5. Application verification of innovative models

5.1. Typical engineering case analysis

5.1.1. Project background and problem diagnosis

The renovation project of a smart water plant in a certain city is typical. The original pipeline network system faces many problems, and frequent pipe bursts are one of the prominent difficulties. This not only affects the continuity of water supply, but also increases maintenance costs and water resource waste [9]. Meanwhile, fluctuations in water quality also pose hidden dangers to residents' water safety, possibly due to aging and corrosion of the pipeline network, as well as a lack of effective water quality monitoring and control measures. These problems seriously constrain the stability and reliability of urban water supply, and there is an urgent need for innovative construction and operation modes to improve the operational efficiency and water supply quality of water plants.

5.1.2. Implementation path of intelligent systems

The implementation path of intelligent systems is crucial in the innovative mode of water plant construction and pipeline operation and maintenance driven by smart water management. The construction of a digital twin platform requires the integration of multiple sources of data, including water plant facility parameters, pipeline network topology, and operational data, to build an accurate virtual model [10]. The deployment of intelligent equipment should be based on the actual needs of the water plant and pipeline network, and intelligent sensors, automation control equipment, etc., should be selected and installed reasonably to achieve real-time monitoring and control of key indicators such as water quality, water quantity, and water pressure. During the system integration phase, it is necessary to ensure smooth data exchange between the digital twin platform and intelligent devices, optimize the system by simulating different operating conditions, improve the operational efficiency of the water plant and the level of pipeline operation and maintenance, and ensure safe and stable water supply.

5.2. Multidimensional evaluation of application effectiveness

5.2.1. Economic cost-benefit analysis

The application of smart water management mode in the construction of water plants and the operation and maintenance of pipeline networks has brought significant economic cost-effectiveness. From the perspective of cost structure, the traditional model accounts for a relatively large proportion of human and material resource consumption, while the smart model has a significant reduction in operation and maintenance labor costs in the later stage, despite the initial investment in technology and equipment. For example, intelligent monitoring devices can provide real-time feedback on pipeline operation data, reducing the frequency of manual inspections. In terms of the investment return cycle, through precise calculation, considering equipment procurement, installation, and commissioning, and later operation and maintenance costs, combined with the water-saving and economic benefits brought by reducing leakage, the smart model can achieve cost recovery and start to make profits after a certain operating period. The water-saving benefits are significant. Through real-time monitoring and precise regulation, water resource waste can be effectively reduced, bringing not only economic value but also environmental and social benefits.

5.2.2. Comprehensive evaluation of social benefits

By establishing an evaluation index system that includes water supply stability, emergency response speed, and public satisfaction, a comprehensive evaluation of innovative models driven by smart water management is conducted. In terms of water supply stability, monitoring data shows that after the application of innovative models, the range of water pressure fluctuations has decreased, and the water quality compliance rate has significantly improved, ensuring stable water use for residents. In terms of emergency response speed, with the help of intelligent monitoring and warning systems, fault location is more accurate, and the time for maintenance teams to arrive at the scene is significantly reduced, minimizing losses caused by water supply interruptions. The results of the public satisfaction survey indicate that residents' satisfaction with water quality, water supply stability, and service response has all increased. From the comprehensive evaluation of social benefits, this innovative model not only improves the operational efficiency and service quality of water plants but also helps to save water resources, reduce social conflicts caused by water supply problems, and has positive significance for urban sustainable development.

5.3. Technical optimization and mode innovation

5.3.1. System iteration upgrade strategy

The distributed model optimization scheme based on federated learning is of great significance in the system iteration and upgrading strategy of smart water management. Through this scheme, data sharing and model training among multiple nodes can be achieved while protecting data privacy. Its advantage lies in the ability to integrate information from different data sources, improving the accuracy and generalizability of the model.

The data storage application of blockchain technology also provides new ideas for smart water management. It ensures the immutability and traceability of data, and can play a key role in water quality monitoring data, pipeline operation and maintenance records, and other aspects. For example, when water quality problems arise, accurately tracing the data records of relevant links can help quickly locate the root cause of the problem, ensure water supply safety, and promote the continuous optimization and upgrading of innovative models for water plant construction and pipeline operation and maintenance.

5.3.2. Standardized construction of operation and maintenance mode

The development of an enterprise standard framework for smart water construction and operation is the core. Clear standards need to be established in terms of construction process, equipment selection and installation, system integration, etc., to ensure construction quality and system compatibility. For example, specifying the construction process parameters for different pipe diameter pipelines in detail. In terms of operation and maintenance, it should cover equipment maintenance cycles, fault diagnosis processes, data monitoring indicators, and other related content. Taking equipment maintenance as an example, develop detailed maintenance schedules and operation guidelines for various types of equipment. At the same time, attention should be paid to the operability and dynamic updating of standards, and timely adjustments and optimizations should be made with the development of technology and the accumulation of practical experience. The formed business promotion model should be based on a standard framework, highlighting advantages and benefits, such as improving operation and maintenance efficiency, reducing costs, etc., attracting more enterprises to adopt, and achieving the widespread application of smart water management models.

6. Conclusion

Smart water management has achieved significant results in the construction and operation of water treatment plants, including improving construction quality and operation efficiency. However, the current technology system has some limitations, such as insufficient edge computing capabilities and model generalization capabilities. Looking ahead to the future, the deep integration of digital twins and metaverse technology will bring new development directions for smart water management. Digital twins can accurately simulate real water systems by constructing virtual models, providing decision support for construction and operation. Metaverse technology can further enhance the immersion and interactivity of virtual environments, optimizing the operational experience of construction and operation. This integration is expected to break through the limitations of existing technologies and promote more efficient and intelligent innovative development of smart water management in the fields of water plant construction and pipeline operation and maintenance.

Disclosure statement

The author declares no conflict of interest.

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