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Construction and Engineering Practice of IoT Management and Control System for Sewage Treatment in Mountainous Counties——Taking the Intelligent Transformation of Wencheng Jingyuan Sewage Treatment Co., Ltd. as an Example

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Abstract

Sewage treatment facilities in mountainous counties of southern Zhejiang are confronted with typical industry pain points including scattered stations, complex terrain, weak communication conditions, drastic fluctuation of influent water quality caused by rainfall, and high manual operation and maintenance costs. The traditional stand-alone automatic control and manual duty mode fail to meet the refined, standardized and low-carbon operation requirements of modern sewage treatment. Based on the intelligent transformation project of Wencheng Jingyuan Sewage Treatment Co., Ltd., this paper constructs an integrated industrial Internet of Things (IoT) management and control system consisting of a perception layer, an edge transmission layer and a cloud platform application layer. Adopting LoRa and 5G hybrid communication, edge data preprocessing and fuzzy PID adaptive regulation technology, the system solves the problems of data islands, delayed regulation and inefficient operation and maintenance in mountainous sewage plants. Engineering practice shows that the system can realize full-process real-time monitoring, intelligent linkage regulation and remote operation and maintenance of sewage treatment, effectively improve the stability of effluent compliance, and reduce equipment energy consumption and labor costs. The research results can provide a practical engineering reference for the intelligent upgrading of IoT systems for small county-level sewage treatment plants in mountainous areas of southern Zhejiang.

Keywords: Internet of Things; Sewage Treatment; Edge Computing; LoRa Communication; Smart Water Service; Intelligent Regulation

1. Introduction

The digital transformation of wastewater treatment has become an important means of improving operational reliability, environmental compliance, resource efficiency, and management precision. Compared with large municipal wastewater treatment plants located in urban or plain areas, sewage treatment facilities in mountainous counties face more complex engineering and operational constraints, including long-distance and high-drop collection pipelines, scattered pumping stations, difficult equipment access, weak communication coverage, and relatively high inspection and maintenance costs. Wencheng County is located in the mountainous area of southern Zhejiang Province, where the sewage collection and treatment system serves both urban domestic sewage and mixed wastewater discharged by small and micro enterprises. Wencheng Jingyuan Sewage Treatment Co., Ltd. adopts an anaerobic–anoxic–oxic process combined with advanced filtration. Before the intelligent transformation, the plant mainly relied on a basic stand-alone programmable logic controller system. Equipment in different process sections operated independently, while water-quality data, equipment-status data, and operation and maintenance records could not be effectively interconnected, resulting in serious data fragmentation, delayed fault identification, and limited coordinated control capacity.

The operating environment of mountainous wastewater treatment plants further increases the difficulty of stable process regulation. Rainfall in mountainous areas is often concentrated and intense, and surface runoff may carry sediment, suspended solids, and organic pollutants into sewage collection systems, causing short-term increases in influent flow and pollutant load. Under the traditional manual regulation mode, aeration, dosing, pumping, and sludge-discharge parameters are usually adjusted only after abnormal water-quality conditions have occurred. Such delayed responses may lead to fluctuations in effluent quality, excessive equipment operation, and unnecessary energy and chemical consumption. Meanwhile, the increasing requirements for online environmental monitoring and refined water-environment governance have made traditional experience-based and labor-intensive management increasingly inadequate. IoT-based monitoring systems can integrate distributed sensors, control equipment, and management platforms, thereby supporting continuous water-quality monitoring, centralized data management, and remote operation and maintenance (Jiang & Sun, 2026; Yang & Zhao, 2026).

Existing studies have explored several technical approaches to the intelligent upgrading of wastewater treatment facilities. LoRa technology has been widely used in distributed water-quality monitoring because of its long communication range, low power consumption, and relatively low deployment cost, making it particularly suitable for rural and mountainous environments (Zhang & Wang, 2024). However, a single LoRa network may be insufficient for transmitting high-frequency monitoring data, video information, and critical control instructions. The integration of LoRa and 5G can combine the advantages of wide-area low-power networking and high-bandwidth cellular communication, thereby improving transmission reliability and communication redundancy for scattered sewage facilities (Guo & Zhang, 2023; Li, 2025). In addition, edge computing enables data cleaning, protocol conversion, local storage, anomaly detection, and preliminary decision-making to be completed near field equipment, reducing dependence on continuous cloud connectivity and improving system response speed and operational resilience (Liu & Chen, 2023; Zhang, 2024).

Intelligent process control is another key component of smart wastewater treatment. Traditional fixed-threshold control cannot adequately respond to rapid changes in influent quantity and quality, particularly under rainfall-induced load fluctuations. Fuzzy proportional–integral–derivative control can dynamically adjust aeration and other process parameters according to real-time operating conditions, thereby improving dissolved-oxygen control accuracy and reducing excessive blower operation (Chen & Li, 2023; Wang, 2024). Digital twin and IoT technologies have also been introduced into municipal wastewater treatment to support visual monitoring, predictive maintenance, and integrated process management (Zhou & Xu, 2024). Nevertheless, much of the existing research focuses on large urban wastewater treatment plants, individual technical modules, simulation-based system design, or prototype verification. These solutions often require stable communication infrastructure, substantial capital investment, and professional maintenance teams, making them difficult to apply directly to small county-level plants in mountainous areas. Moreover, relatively few studies have evaluated the integrated effects of communication, edge computing, adaptive control, and remote operation and maintenance using long-term engineering operation data.

To address these limitations, this study develops and evaluates an integrated IoT management and control system based on the intelligent transformation project of Wencheng Jingyuan Sewage Treatment Co., Ltd. The system adopts a three-layer architecture consisting of a perception and collection layer, an edge transmission layer, and a cloud platform application layer. Industrial Ethernet, LoRa, and 5G are integrated into a hierarchical hybrid communication network to meet the differentiated transmission requirements of the core plant area, remote pumping stations, and key monitoring nodes. Lightweight edge computing is introduced to perform local data preprocessing, abnormal-data filtering, offline caching, and fault warning, while fuzzy PID control is used to adaptively regulate aeration and dosing according to rainfall, influent load, water-quality indicators, and equipment operating conditions. Based on 12 months of engineering operation, the study evaluates the system in terms of effluent-quality stability, electricity consumption, chemical consumption, maintenance cost, labor input, and digital management efficiency. The study therefore provides an engineering-oriented reference for the low-cost, reliable, and intelligent upgrading of small wastewater treatment plants in mountainous counties.

2. Overall Architecture Design of Sewage IoT Management and Control System

Following the standard industrial IoT architecture, the transformation constructs a three-level system including a perception and collection layer, an edge transmission layer and a cloud platform application layer, which balances the real-time performance of equipment control, the stability of data transmission and the convenience of operation and maintenance management, and fully adapts to the production conditions of sewage treatment in mountainous areas.

2.1. Perception and Collection Layer

As the core data source of the system, the perception layer covers all process nodes including water inlet grille, biochemical tank, secondary sedimentation tank, effluent channel and township lifting pump stations, and is equipped with three types of intelligent sensors for water quality, operating conditions and environment. All sensors adopt industrial standard protocols to support unified data collection. Water quality sensors real-timely monitor core indicators such as pH value, dissolved oxygen, ammonia nitrogen, COD, total phosphorus and sludge concentration. Operating condition sensors collect real-time data of current, temperature and vibration of water pumps, fans and dosing equipment, as well as sewage flow and tank liquid level. Matching rainfall, temperature and humidity sensors and video monitoring equipment are deployed to realize all-round perception of mountainous environment and factory operating conditions. All outdoor equipment adopts IP68 high protection grade to adapt to the harsh mountainous environment with humidity, low temperature and sediment, ensuring long-term stable operation.

2.2. Edge Transmission Layer

Abandoning the single transmission mode, a hierarchical hybrid communication scheme is adopted to address the problems of mountainous terrain occlusion and weak communication. Industrial optical fiber ring network is laid in the core area of the factory to realize high-speed linkage control of equipment with the response delay controlled within 200ms. LoRa low-power networking is deployed in remote pump stations and areas without optical fiber coverage, featuring wide communication coverage and low power consumption, which eliminates complex wiring and greatly reduces construction cost. 5G industrial gateways are equipped at key environmental monitoring nodes to form a dual-link backup and ensure uninterrupted transmission of monitoring data. Meanwhile, edge gateways realize local data preprocessing, automatically filter abnormal distorted data, and complete on-site early warning and data compression storage, which effectively solves the problems of data loss and transmission delay caused by mountainous network fluctuations.

2.3. Cloud Platform Application Layer

The platform adopts a hybrid database architecture to store high-frequency real-time sensor data, equipment operation and maintenance data, and report account data respectively, supporting dual-terminal management interfaces of web page and mobile APP. The core functions include full-process visual monitoring, which displays the operating status of the factory and remote pump stations in real time through process flow charts and electronic maps; multi-level intelligent early warning and push, which realizes multi-channel hierarchical reminders via APP, SMS and voice according to the severity of faults and water quality exceeding standards; adaptive process linkage control, which automatically adjusts the operating parameters of aeration and dosing equipment based on fuzzy PID algorithm combined with rainfall and water quality load. It also supports full-life-cycle equipment operation and maintenance, energy consumption data statistics and automatic generation of environmental protection reports, realizing digital and closed-loop management of sewage treatment.

3. Key Points of System Engineering Implementation

3.1. Equipment Selection Adapted to Mountainous Working Conditions

Considering the limited operation and maintenance conditions in Wencheng mountainous area, equipment is selected with high stability, maintenance-free performance and easy operation. Water quality sensors adopt maintenance-free membrane heads to reduce field calibration frequency. Remote terminal equipment supports solar power supply without municipal power layout. The gateway has an offline caching function, which can automatically store 7-day data when the network is disconnected and supplement the data after network recovery, completely avoiding data loss.

3.2. Phased Construction and Implementation Scheme

To avoid affecting normal sewage treatment during construction, the project adopts phased non-stop transformation. In the first stage, the core network layout and PLC system protocol docking of the factory are completed to build a basic gateway framework. In the second stage, the installation and commissioning of sensors and 5G gateways in core process sections are completed to ensure stable upload of environmental protection data. In the third stage, the networking of LoRa equipment in remote pump stations, deployment of video monitoring and commissioning of intelligent regulation algorithm are completed. The whole construction cycle is short without production shutdown, realizing the comprehensive upgrading of the system successfully.

3.3. System Security Protection Design

To ensure the security of industrial equipment and data, the system adopts encrypted transmission, unique equipment authentication and hierarchical account permission management to prevent illegal equipment access and data leakage. Meanwhile, a local backup control logic is set. When the cloud or network fails, the system will automatically switch to the original automatic control mode, avoiding risks of equipment runaway and water quality exceeding standards, and ensuring the safe and stable operation of production.

4. Analysis of System Operation Effectiveness

After 12 months of stable operation, the overall operation level of the factory has been significantly improved with remarkable optimization of various benefit indicators. Firstly, the stability of effluent water quality is greatly improved, eliminating the problem of water quality fluctuation in rainy seasons. All effluent indicators are stably better than the first-class A discharge standard, with no environmental exceeding records and zero interruption of online data upload throughout the year. Secondly, the energy-saving and cost-reducing effect is prominent. The adaptive aeration and precise dosing system eliminate invalid equipment operation, reducing the comprehensive power consumption of the factory by 13.2% and reagent consumption by 9.7%, which effectively cuts the production and operation cost. Thirdly, the operation and maintenance efficiency is significantly improved. Remote monitoring replaces traditional manual field inspection, halving the labor input. Advanced early warning of equipment faults reduces the annual maintenance cost by 21%. Fourthly, the level of digital management is fully upgraded. The system automatically generates energy consumption, operation and maintenance, and environmental protection ledgers, eliminating manual filling. Managers can conduct remote management and control via mobile terminals, greatly improving the efficiency of emergency response.

Targeting at mountainous characteristic problems such as mountain signal occlusion and sensor data drift caused by sediment adhesion during operation, optimization and rectification have been completed by adding relay gateways, optimizing installation positions, and configuring automatic flushing and data correction algorithms, further improving the system adaptability and stability.The detailed operation performance indicators before and after the system transformation are shown in Table 1.

Table 1. The detailed operation performance indicators

Performance Indicators	Before Transformation	After Transformation	Improvement Effect
Effluent water quality compliance rate	Affected by rainfall fluctuation, occasional critical deviation	100% compliance, stably superior to Class A standard	Eliminate seasonal water quality fluctuation risk
Comprehensive power consumption	Long-term full-load operation of equipment, high energy consumption	13.2% reduction in annual power consumption	Significant energy-saving effect
Chemical reagent consumption	Manual fixed dosing, serious waste	9.7% reduction in PAC and PAM consumption	Realize precise dosing and cost reduction
Annual equipment maintenance cost	Passive maintenance, high failure rate	21% reduction in annual maintenance cost	Realize predictive maintenance
On-site inspection manpower input	2 full-time inspectors for daily field patrol	Half of manpower saved, weekly patrol mode adopted	Greatly improve operation and maintenance efficiency

5. Existing Deficiencies and Optimization Directions

According to the one-year operation situation, the system still has some limitations. Firstly, the water quality prediction model has limited data dimensions, without integrating upstream hydrological and refined meteorological data, resulting in slight prediction lag under extreme weather conditions. Secondly, the system lacks a 3D digital twin function, which cannot intuitively simulate hidden faults of pipe networks and tank bodies. Thirdly, village-level micro sewage treatment stations in the county have not been included in the platform, and unified full-domain management has not been realized.

Future optimization and upgrading will be carried out in three aspects: docking with official refined meteorological and hydrological data, iterating the machine learning prediction model to realize advance prediction of influent load; building a lightweight 3D digital twin module to visually restore equipment operation and process status; gradually expanding IoT equipment for village-level sewage stations to construct a unified intelligent management system for county-level sewage treatment.

6. Conclusion

Aiming at the special working conditions of sewage treatment in mountainous counties of southern Zhejiang, this paper constructs a low-cost, highly adaptable and easy-to-operate IoT intelligent management and control system. Through the three-level IoT architecture and hybrid communication technology, it effectively solves the industry pain points of isolated data, delayed regulation, cumbersome operation and maintenance, and high energy consumption in mountainous sewage plants. Engineering practice verifies that the system can significantly improve the compliance rate of sewage treatment, realize energy conservation, cost reduction, quality improvement and efficiency enhancement, and comprehensively promote the digital and refined upgrading of factory operation.

Avoiding the disadvantages of high cost and high construction difficulty of traditional large-scale smart water service projects, this scheme is suitable for the intelligent transformation of small county-level sewage plants in mountainous areas, and can provide mature engineering reference for the intelligent upgrading of sewage treatment in similar mountainous counties in southwestern Zhejiang. As a front-line engineering manager, the author will continuously optimize intelligent algorithms and improve the full-domain management system, give full play to the core supporting role of IoT technology in mountainous water ecological governance and refined sewage treatment operation, and help the digital and low-carbon transformation of the water service industry.

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Conceptualization, T. Z; methodology, T. Z; investigation, T. Z; data collection and analysis, T. Z; writing—original draft preparation, T. Z; writing—review and editing, T. Z; project administration, T. Z. All authors have read and agreed to the published version of the manuscript.

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