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Research on the Application of Internet of Things Technology in Smart Water Operation of Mountain Urban-Rural Integrated Water Supply

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Abstract

Wencheng County is a typical mountainous area in southern Zhejiang Province, characterized by scattered water supply stations and long pipelines. The traditional manual operation mode leads to delayed water quality supervision, severe pipeline leakage, high labor costs for rural water supply, and lack of digital support for corporate management. The author currently serves as Deputy General Manager of Wencheng Water Affairs Co., Ltd., Wenzhou Public Utilities Development Group, and has overall responsibility for the construction, launch and daily operation of the local IoT smart water project. Combining frontline experience in engineering management and corporate operation, this paper introduces an integrated IoT construction framework. With data cases, it elaborates four core application scenarios including water quality control, DMA leakage control, remote operation of rural water supply and smart revenue management. It sorts out the bottlenecks of IoT operation in mountainous areas and proposes targeted optimization schemes, providing practical references for the implementation of IoT projects in similar mountainous water utilities.

Keywords: Internet of Things; Smart Water; Urban-Rural Integrated Water Supply; DMA Zoning; Pipeline Leakage Control

1. Introduction

In recent years, Zhejiang Province has vigorously promoted the integration of urban and rural water supply and the digital transformation of rural drinking water services. Under this policy and industrial background, Internet of Things (IoT), NB-IoT, intelligent sensing, remote monitoring and big data analysis have become important technical tools for water enterprises to improve operational efficiency, reduce management costs and realize refined water supply governance.

Existing studies have shown that IoT technology can support real-time monitoring, intelligent scheduling, online early warning and data-based decision-making in water supply systems, thereby improving the responsiveness and controllability of water operation management (Pang, 2025; Yang & Wang, 2025). For county-level water enterprises, especially those located in mountainous areas, the application of IoT technology is not only a technical upgrading measure, but also an important path to solve long-standing problems such as scattered facilities, insufficient manual inspection capacity, delayed emergency response and high operating costs.

Wencheng County is dominated by mountainous terrain, with more than 200 water plants and village-level water supply stations, as well as over 1,000 kilometers of water supply pipelines. A large number of water sources, reservoirs, booster pump stations, water production facilities and terminal water supply points are distributed in remote mountain valleys, which makes daily operation and maintenance difficult. Compared with urban centralized water supply systems, mountainous water supply systems are characterized by long pipeline routes, dispersed monitoring points, poor accessibility, unstable communication conditions and limited power supply in some areas. These objective conditions significantly reduce the efficiency of traditional manual patrols and increase the difficulty of timely fault discovery and emergency disposal. Previous research on village and town water supply has also pointed out that IoT-based monitoring and control systems can effectively improve the management efficiency of rural water supply networks, especially in scenarios involving dispersed facilities and weak operation capacity (Lei & Cheng, 2024; Liu, 2026).

Before the digital transformation, Wencheng Water Affairs faced several prominent management pain points. First, water quality inspection mainly relied on regular manual sampling, which made it difficult to provide real-time warnings for sudden water quality deterioration during flood seasons or extreme weather events. Second, online flow and pressure monitoring devices were insufficiently deployed in the pipe network, and hidden leakage detection mainly depended on manual listening and experience-based judgment, resulting in a relatively high production-sales difference rate and serious invalid water loss. Studies on DMA-based leakage control indicate that district metering, pressure monitoring and data-driven leakage warning can provide a more precise basis for identifying abnormal water loss and improving leakage governance efficiency (Chen, 2025; Zhang et al., 2025). Third, mountain booster pump stations and village-level water supply stations traditionally required full-time on-site personnel, which led to high labor expenditure and low operation efficiency. Fourth, data related to water production, pipe network operation, water quality, energy consumption and user metering were relatively isolated, making it difficult to support accurate cost accounting, scientific scheduling and integrated decision-making.

In response to these practical problems, the author, as Deputy General Manager in charge of relevant work, took the lead in promoting the construction of an IoT-based management system covering the whole chain of raw water, water production, pipe network transmission, rural water supply and user metering. Through the deployment of intelligent sensors, online water quality monitoring terminals, flow and pressure monitoring equipment, remote control devices and smart metering facilities, the system has gradually realized 24-hour online monitoring, remote regulation, abnormal early warning and closed-loop operation management. Relevant local practice also shows that Wencheng Water Affairs has adopted multiple measures to reduce the pipeline leakage rate and improve refined pipe network management (Wenzhou State-owned Assets Supervision and Administration Commission, 2026). Based on the author's practical experience in project coordination, engineering implementation and cost control, this paper systematically analyzes the implementation effects, existing problems and improvement ideas of IoT engineering in mountainous county water supply scenarios. The study aims to provide a practical reference for the digital transformation of rural drinking water management and the construction of low-cost, lightweight and replicable smart water systems in mountainous counties.

2. Integrated IoT Construction System for Mountain Water Utilities

The project adopts a three-layer architecture consisting of perception terminals, hybrid communication and smart platform, adapting to mountainous terrain and weak communication signals while meeting the demands of low power consumption, outdoor durability and low operation cost.

2.1. Full-Coverage Deployment of IoT Perception Terminals

Monitoring devices are deployed at key nodes of the whole water supply process. Solar power modules are installed for field sites without municipal power supply. The deployment list is shown in Table 1.

Table 1. Deployment List of IoT Perception Terminals

Terminal Type	Deployment Location	Core Function	Deployment Scale
Water Quality Monitoring Terminal	Raw water intake, water plant outlet, pipe network terminal, village water supply station	Real-time monitoring of pH, turbidity, residual chlorine; automatic early warning for exceeding standards	86 sets
Pipe Flow & Pressure Terminal	Trunk pipelines at DMA zoning boundaries	Collect flow and pressure; calculate production-sales difference; locate leakage points	160 sets (7 primary DMA zones, 29 secondary DMA zones)
NB-IoT Smart Water Meter	All urban and rural water users	Remote meter reading, abnormal water consumption identification, remote valve closing	More than 32,000 units
Pump Station PLC Automatic Control Terminal	Urban water plants and mountain booster pump stations	Variable frequency regulation of water pumps, unit fault monitoring, unattended operation	19 sets
Integrated Rural Water Supply Terminal	122 village-level water supply stations	Water level monitoring, disinfection equipment control, video surveillance, fault alarm	122 sets

2.2. Hybrid Communication Scheme for Mountainous Areas

A layered transmission strategy is formulated to address uneven signal coverage. NB-IoT is adopted in stable urban and town areas with low power consumption and low communication fees. Signal gain antennas and 4G DTU are equipped at deep mountain canyons with weak signals. Optical fiber wired transmission is applied in water plants and dispatching centers to ensure stable transmission of video and control instructions. All data are transmitted in encrypted form to guarantee the security of water operation data.

2.3. Group Unified Smart Water Management Platform

A dedicated IoT platform for Wencheng is built based on the cloud infrastructure of Wenzhou Public Utilities Group Water Affairs, with core functions as follows: First, the time-series database stores historical data for more than 3 years to support leakage tracing and cost analysis. Second, customized early warning thresholds are set, and abnormal information is pushed synchronously to computers and mobile mini-programs. Third, all monitoring points, water plants and leakage points are displayed on an integrated GIS map. Fourth, subsystems of charging, operation maintenance and safety production are interconnected to eliminate data silos, supporting scheduling, maintenance and business management on one single platform.

3. Engineering Application of IoT in Water Operation

Combined with the work of operation, project and maintenance management, IoT reshapes the mountain water supply management model from four dimensions.

3.1. Precise Leakage Control Based on DMA Zonal IoT Metering

Old pipe networks in Wencheng lack complete archives, making traditional manual leakage detection inefficient. The platform compares the inflow and outflow data of each zone and identifies hidden leakage through the fluctuation of minimum night flow, narrowing down leakage areas with pressure data. Key indicators before and after transformation are shown in Table 2.

Table 2. Comparison of Pipeline Leakage Control Indicators

Assessment Indicator	Before Transformation	After Platform Operation
Average leakage repair duration	72h	6h
Annual number of hidden leakage points detected	Less than 120	350
Comprehensive pipeline leakage rate	18.2%	12.7%

The author took the lead in establishing a water-saving assessment mechanism for each zone. The business department exports monthly production-sales difference data from the IoT system to quantify the performance of maintenance teams, continuously reducing water waste and maintenance investment.

3.2. 24-Hour Online Monitoring to Ensure Water Quality Safety

Mountain floods easily cause sudden rise of raw water turbidity. Alternate manual sampling leads to delayed risk response. Water quality sensors collect full-process data round the clock and push early warnings once indicators exceed limits, allowing dispatchers to adjust water production processes timely. The platform stores complete water quality files, which can be quickly retrieved for environmental supervision and public complaint handling, standardizing water quality management greatly.

3.3. Remote Automatic Control of Pump Stations to Cut Labor Costs

Before transformation, 30 full-time caretakers were required for all village water supply stations. The IoT system realizes linkage start-stop of water pumps and disinfection equipment according to water levels, with automatic fault alarms. After upgrading, only 5 mobile inspection teams are arranged, cutting the number of caretakers by half. The author organized the business department to summarize monthly water volume, chemical and power consumption data from the IoT system, accurately calculating the operation cost of rural water supply and optimizing the annual budget.

3.4. NB-IoT Smart Meters Improve Revenue and Inspection Capacity

In the past, manual meter reading in remote villages took up to one month, resulting in delayed water fee recovery. After full replacement of IoT water meters, water consumption data are uploaded daily and water bills are generated automatically. The platform marks users with zero or sharply fluctuating water consumption, and inspectors conduct on-site investigations on water theft and private pipeline connection. Remote valve closing for arrears effectively improves water fee recovery and corporate cash flow.

4. Deficiencies of IoT System in Mountain Operation

Years of on-site management reveal four prominent problems under mountain geographical and climatic conditions: First, uneven communication coverage. 4G and NB-IoT signals are weak at deep mountain pipelines and remote water supply stations, causing frequent offline terminals. Installation of signal amplifiers increases construction cost. Second, fast aging of field equipment. Large temperature difference, high humidity and heavy rain in mountainous areas lead to corrosion and line aging of sensors and solar modules. The failure rate is higher than that in urban areas, bringing continuous replacement and maintenance expenditure. Third, insufficient data fusion depth. Only basic interconnection is realized among monitoring, marketing and GIS systems. Advanced functions such as water consumption prediction and intelligent peak shaving are missing, failing to fully exploit the commercial value of massive monitoring data. Fourth, shortage of interdisciplinary technical talents. Frontline maintenance staff are skilled in pipeline repair but unable to debug IoT equipment. Business managers lack data analysis ability, limiting the value of digital management.

5. Optimization Countermeasures for IoT System

Targeted improvement plans are formulated in line with the company′s medium and long-term operation planning:

Hierarchical optimization of communication network: Deploy LoRa relay equipment in signal-poor mountainous areas to aggregate data before unified upload; promote operators to build more mountain base stations; adopt dual power supply of solar energy and backup power for core monitoring points of water sources and trunk pipelines to reduce offline risks under extreme weather.

Full-lifecycle standardized equipment management: Prioritize IP68 anti-corrosion terminals in subsequent procurement and establish equipment service ledgers. The business and maintenance departments jointly compile annual equipment renewal budgets in advance to predict aging faults and reduce monitoring gaps.

Deepen multi-system data fusion: Improve big data analysis models to build water consumption load prediction based on years of flow data for energy-saving scheduling of water plants. Refine classified statistics of production-sales difference to distinguish losses caused by leakage, metering error and water theft, generating integrated business reports combining water quality, energy consumption and revenue data.

Hierarchical digital training: Carry out practical training on terminal installation and troubleshooting for maintenance teams; organize special training on platform data analysis for business and dispatch staff; establish long-term technical support from equipment manufacturers to rapidly solve software and hardware faults.

6. Comprehensive Application Effects of the Project

After full operation of the IoT platform, remarkable benefits are achieved in production and operation: First, prominent water saving and cost reduction. Precise leakage control based on DMA zoning reduces pipeline leakage year by year, cutting hundreds of thousands of tons of water waste annually, together with synchronous decline in chemical, power and pipeline maintenance costs to boost corporate profits. Second, significant reduction of operation labor. Unattended transformation of rural water supply stations and pump stations greatly reduces the frequency of manual inspections and labor expenditure. Third, upgraded water supply safety guarantee. Water quality and pipeline faults shift from post-repair to pre-warning, greatly improving emergency disposal efficiency in flood seasons, with zero major water supply accidents over years. Fourth, digital transformation of business management. Automatic meter reading, water consumption inspection and zonal assessment are fully implemented. Real-time visualized business data improve the efficiency of water fee recovery and water supervision, supporting the long-term operation of urban-rural integrated water supply.

7. Conclusion

Restricted by terrain, pipe network and maintenance conditions, traditional extensive manual management cannot meet the high-quality development requirements of mountain urban-rural water supply. Supported by full-domain perception, remote transmission and intelligent analysis, IoT technology systematically addresses core management pain points including water quality supervision, pipeline leakage control, rural water supply operation and revenue management.

The practice in Wencheng proves that smart water IoT construction is not a one-time equipment installation project. Continuous optimization of communication, equipment, data and talent supporting systems is required according to mountain geographical characteristics. In future work, based on the post of Deputy General Manager, the author will further tap the application value of IoT monitoring data, optimize intelligent water supply scheduling, improve leakage assessment indicators and reduce rural water supply operation costs, and continuously explore the integration path of IoT, big data and water service business to provide engineering practice support for sustainable development of smart water in counties.

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

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