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Digital Empowerment of Mountainous Rural-Urban Integrated Water Supply: Construction and Practice of a Whole-Process IoT Sensing System in Wencheng County

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Abstract

Against the backdrop of Zhejiang Province's comprehensive advancement of rural drinking water safety digital upgrading and urban-rural water supply integration, mountainous counties face unique operational bottlenecks caused by fragmented water supply facilities, complex terrain and long scattered pipe networks. Taking Wencheng County—a typical mountainous water supply area in southern Wenzhou—as the research object, this paper starts from the full-cycle operation and management demands of county-level water enterprises. Combined with the actual construction and long-term stable operation of the local intelligent water supply digital system, this study designs a full-chain IoT sensing system adapted to mountain terrain, featuring multi-layer communication networking and cloud-based integrated operation platform. Differentiated from traditional single-equation monitoring schemes, the system realizes synchronized perception of raw water sources, water production workshops, regional pipe networks, village-level water supply stations and end-user metering. This paper systematically analyzes practical application effects in four core scenarios including full-process water quality early warning, DMA partition accurate loss control, unattended remote operation of scattered water supply facilities and intelligent user revenue management. Based on multi-year field operation records, it summarizes targeted operational obstacles brought by mountain climate and signal conditions, and proposes multi-dimensional optimization strategies covering communication networking, outdoor equipment durability, big data deep mining and compound talent training. The research conclusions can provide differentiated digital transformation references for mountainous counties with similar terrain and water supply layout, and offer feasible optimization ideas for the refined operation of urban-rural integrated water supply projects.

Keywords: Internet of Things; Whole-process Perception; Urban-rural Integrated Water Supply; Mountain Water Supply; DMA Partition Pipeline Loss Control; Digital Refined Operation

1. Introduction

Rural drinking water safety is a core livelihood project, and digital transformation has become an essential path to solve the long-standing extensive management mode of mountain water supply. In recent years, the Internet of Things (IoT) has been increasingly applied to water supply systems, especially in intelligent monitoring, optimal scheduling, network control, leakage warning, and smart water management (Pang, 2025; Yang & Wang, 2025; Zhao, 2026). Existing studies have shown that IoT-based water supply systems can improve real-time perception, data-driven decision-making, and operational efficiency by integrating sensing equipment, communication networks, and digital management platforms (Cheng, 2023; Jamadarkhani, 2025). For rural and village-level water supply scenarios, IoT technology is particularly valuable because it can reduce dependence on manual inspection and enhance the continuity of operation and maintenance in geographically dispersed areas (Lei & Cheng, 2024; Liu, 2026).

Restricted by alpine valley terrain, Wencheng County owns over 200 decentralized water plants and village-level water supply facilities, with a total water supply pipeline mileage exceeding 1,000 km. Most water supply nodes are distributed in remote mountainous areas with inconvenient transportation, which greatly reduces the efficiency of manual daily patrol, fault emergency disposal, and regular water quality sampling. Similar rural water supply systems often face difficulties such as scattered facilities, weak monitoring capacity, delayed emergency response, and high operation and maintenance costs, which further highlights the necessity of constructing intelligent water supply platforms adapted to mountainous and rural contexts (Lei & Cheng, 2024; Liu, 2026).

Before digital transformation, Wencheng Water Affairs encountered multiple prominent operational pain points. First, water quality risk prevention relied on periodic manual sampling and laboratory testing; sudden turbidity surges and residual chlorine abnormalities during flood seasons could not trigger real-time early warnings, leading to passive post-event disposal. Second, pipe network operation lacked full-flow real-time monitoring equipment; hidden pipeline leakage mainly depended on manual acoustic detection, resulting in a high water production-sales difference rate and massive invisible water resource waste. Leakage control and early warning have become important components of smart water management, and studies have explored methods such as district metered area management and data-field clustering to identify abnormal water consumption and leakage risks more effectively (Chen, 2025; Zhang et al., 2025). Third, numerous mountain booster pump stations and village water supply stations required full-time on-site staff, forming a heavy long-term labor cost burden. Fourth, isolated data silos existed among water production, pipe network operation, and user water consumption modules; cost accounting, regional water supply scheduling, and performance assessment lacked unified data support.

To address the above difficulties, Wencheng Water Affairs, under the Wenzhou Public Utilities Group, built a full-chain IoT digital operation platform covering all links from raw water intake to end-user water consumption. The system realizes 24-hour uninterrupted equipment status perception, remote linkage regulation, and automatic abnormal information push. According to the practical experience reported by the Wenzhou State-owned Assets Supervision and Administration Commission (2026), Wencheng Water Affairs has adopted multiple measures to reduce the pipeline leakage rate, which provides a realistic basis for examining the operational effectiveness of smart water construction in mountainous counties. Based on long-term front-line business practice, this paper sorts out the overall construction logic of the mountain-adapted IoT system, verifies practical benefits through long-term operational statistical data, analyzes typical operational barriers in mountain scenarios, and puts forward operable improvement plans for the long-term optimized operation of intelligent water supply systems.

2. Overall Construction Framework of Mountain-Adapted Full-Chain IoT Sensing System

Fully considering the weak signal coverage, large temperature and humidity difference and insufficient municipal power supply in mountainous areas, the project constructs a three-level collaborative architecture of multi-type field sensing terminals, multi-mode hybrid communication transmission and group cloud integrated intelligent operation platform, with the design goals of low power consumption, strong outdoor environmental adaptability and low long-term operation and maintenance cost.

2.1. Full-node Layout of Diversified Sensing Terminals with Solar Supplementary Power Supply

Sensing terminals are deployed at all key control nodes throughout the whole water supply process. For mountain sites without stable municipal power supply, independent solar power supply modules with energy storage batteries are equipped to ensure continuous online monitoring under power failure conditions. The specific layout specifications of all sensing devices are shown in Table 1.

Table 1. Layout Configuration of Full-Chain IoT Sensing Terminals

Equipment Category	Installation Nodes	Core Monitoring & Control Functions	Total Deployment Quantity
Multi-index Water Quality Sensing Equipment	Raw water intake points, finished water outlets of water plants, pipe network terminal monitoring points, village centralized water supply stations	Real-time continuous monitoring of pH value, water turbidity, residual chlorine content; automatic threshold-crossing early warning and data storage	86 sets
Pipe Network Flow & Pressure Integrated Collectors	Boundary pipelines of each DMA partition area	Real-time collection of pipeline flow and static pressure data; automatic calculation of regional water supply inflow-outflow difference; auxiliary positioning of hidden leakage sections	160 sets (7 primary DMA large partitions, 29 secondary fine partitions)
NB-IoT Intelligent Remote Water Meters	All urban and rural resident and non-residential water users	Daily automatic remote meter reading, abnormal water consumption recognition, remote valve	More than 32,000 units

		shutoff for arrears	
Pump Station PLC Intelligent Control Terminals	Central urban water plants, mountain distributed booster pump stations	Variable frequency remote adjustment of water pumps, real-time online diagnosis of unit operating faults, unattended automatic operation	19 sets
Pump Station PLC Intelligent Control Terminals	122 village-level centralized water supply facilities	Real-time reservoir water level monitoring, linkage control of disinfection equipment, video real-time monitoring, automatic fault alarm push	122 sets

2.2. Multi-mode Hybrid Communication Transmission Strategy for Mountain Signal Differentiation

A hierarchical data transmission scheme is formulated targeting the uneven distribution of communication signals in mountain valleys:

(1) Flat urban and town areas with stable cellular signals adopt NB-IoT narrowband communication, which features low power consumption and low long-term communication service fees, suitable for regular small-volume sensing data upload;

(2) Deep mountain canyon sections with weak base station signals are equipped with signal gain antennas and 4G DTU transmission modules to enhance signal receiving strength and reduce offline frequency of field terminals;

(3) Central water plants and group dispatching centers adopt optical fiber wired transmission to guarantee stable transmission of high-capacity video monitoring signals and remote pump linkage control instructions.

2.3. Group Cloud Integrated Intelligent Water Operation Platform

Relying on the unified cloud infrastructure of Wenzhou Public Utilities Group Water Sector, a special IoT digital operation platform exclusive to Wencheng County is built, with core functional modules as follows:

(1) Long-cycle time-series database: Supports storage and archiving of all equipment historical operation data for more than 3 years, providing data basis for long-period pipeline leakage traceability and regional water supply cost statistical analysis;

(2) Customized multi-dimensional early warning system: Support independent setting of early warning threshold values for water quality indicators, pipeline pressure, real-time flow and equipment operating status; abnormal alarm information can be synchronously pushed to PC operation terminals and mobile WeChat mini-programs for on-duty staff;

(3) GIS one-map visualization module: Integrates all water quality monitoring points, pump stations, pipe network boundary collectors and leakage early warning areas into a unified geographic information map to realize visual overall scheduling;

(4) Cross-system data interconnection module: Realizes data docking among charging marketing, operation and maintenance work order dispatching, safety production supervision and IoT sensing subsystems, eliminates data isolation, and realizes one-stop completion of scheduling command, maintenance arrangement and business performance statistical analysis on a single platform.

3. Core Practical Scenarios and Operation Effects of IoT Digital System in Wencheng Water Supply

Combined with daily business performance assessment, regional operation cost control and urban-rural overall coordination work, the IoT whole-process sensing system reconstructs the refined management model of mountain water supply from four core business dimensions.

3.1. DMA Partition Intelligent Loss Control to Reduce Invisible Pipeline Water Waste

The historical pipe network of Wencheng County lacks complete electronic archives, and the traditional manual leakage detection mode has low efficiency and long disposal cycle. The platform compares real-time inflow and outflow data of each DMA partition area collected by boundary flow collectors, identifies potential leakage hidden dangers through the fluctuation law of minimum night flow, and combines pipeline pressure change data to continuously narrow down the scope of leakage sections, guiding maintenance teams to carry out targeted fixed-point repair. The core operation indicators before and after digital reconstruction are compared in Table 2.

Table 2. Comparison of Pipe Network Loss Control Effect Indicators Before and After Digital Transformation

Assessment Indicator	Pre-digital Transformation Stage	Stable Operation Stage of IoT Platform
Average leakage repair duration	72 h	6 h
Annual number of hidden leakage points located	Less than 120	350
Comprehensive pipeline leakage rate	18.2%	12.7%

The business department extracts monthly production-sales difference data of each DMA partition from the platform, formulates differentiated water-saving assessment indicators for maintenance teams, quantifies team operation performance, effectively reduces overall water resource waste and cuts long-term pipeline maintenance investment.

3.2. Full-Time Continuous Water Quality Online Monitoring to Secure Urban and Rural Drinking Water Safety

Mountain flood season rainfall and soil erosion easily cause sudden sharp rise of raw water turbidity. Discrete periodic manual sampling cannot capture sudden water quality risks in a timely manner. Full-process water quality sensing equipment collects water quality data uninterruptedly 24 hours a day; once any monitoring index exceeds the safety threshold, the system automatically triggers an early warning. Dispatchers can adjust flocculation agent dosing and disinfection process parameters in real time, and arrange staff to conduct on-site verification synchronously. The platform automatically stores complete full-cycle water quality monitoring records, which can be quickly exported for water conservancy and environmental supervision inspection and public water quality complaint handling, realizing standardized traceable whole-process water quality management.

3.3. Remote Automatic Linkage Control of Scattered Water Supply Facilities to Cut Labor Input

There are more than 200 scattered village-level water supply stations distributed across mountainous areas. Before digital upgrading, the company needed to arrange 30 full-time on-site caretakers for daily equipment inspection and operation, bringing huge fixed labor expenditure. The IoT system realizes automatic linkage start-stop of water pumps and disinfection equipment according to reservoir upper and lower water level limits, and automatically pushes fault alarms once equipment abnormal operation occurs. After system reconstruction, only 5 mobile comprehensive inspection teams are deployed to cover all mountain water supply nodes, cutting the number of full-time on-site staff by nearly half. The business department sorts out monthly water supply volume, medicament consumption and power consumption data exported from the platform, accurately calculates the independent operation cost of each village water supply station, and provides reliable data support for the formulation of annual enterprise operation budgets.

3.4. NB-IoT Intelligent Water Meters Optimize User Revenue Management and Anti-theft Water Inspection

Traditional manual centralized meter reading in remote mountain villages takes nearly one month to complete the whole region, resulting in serious delay of water fee recovery and tight enterprise capital flow. After the full popularization of NB-IoT intelligent remote water meters, all user water consumption data are automatically uploaded to the platform every day, and the system generates user water bills automatically. The platform marks abnormal user water consumption data such as long-term zero water use and sharp fluctuation of water consumption; business inspectors conduct targeted on-site investigation to crack down on illegal water theft and private pipeline connection behaviors. The remote valve shutoff function for arrears users effectively raises the overall water fee recovery rate and optimizes the enterprise’s cash circulation efficiency.

4. Practical Restricting Factors of IoT Digital System Under Mountain Operation Environment

After years of continuous field operation and maintenance, four prominent restrictive problems caused by mountain unique geographical environment and climatic conditions are summarized:

(1) Uneven communication signal coverage: Deep mountain buried pipelines and remote isolated village water supply stations are covered by weak 4G and NB-IoT base station signals, leading to frequent offline status of field sensing terminals. Installing signal amplifiers and relay equipment increases the initial construction investment of the project.

(2) Fast aging damage speed of outdoor field equipment: Mountain areas feature large temperature difference between day and night, high air humidity and long-term heavy fog weather, which easily cause shell corrosion and internal circuit aging of outdoor sensors and solar power supply modules. The failure rate of field equipment is far higher than that of urban areas, generating continuous equipment replacement and maintenance costs every year.

(3) Insufficient depth of cross-system data mining and application: At present, the system only realizes basic data interconnection among IoT sensing, charging marketing and GIS pipe network modules. Advanced data analysis functions such as regional water consumption load prediction and intelligent pipe network peak-shaving scheduling have not been developed, failing to fully exploit the deep business value of massive long-term monitoring data.

(4) Severe shortage of compound interdisciplinary technical talents: Front-line maintenance workers are proficient in pipeline repair and civil engineering construction, but lack professional capabilities in IoT terminal equipment debugging and fault elimination; enterprise business and management staff cannot independently conduct multi-dimensional data analysis relying on the platform, limiting the full release of digital management efficiency.

5. Targeted Optimization Strategies for Mountain IoT Intelligent Water Supply System

Combined with the medium and long-term refined operation planning of Wencheng Water Affairs, operable multi-dimensional improvement plans are proposed for the four major restricting factors above:

(1) Hierarchical optimization of mountain communication network layout: Deploy local LoRa signal relay equipment in deep mountain areas with extremely weak signals to collect decentralized terminal data uniformly before upward transmission; continuously cooperate with communication operators to promote the construction of dedicated mountain base stations; adopt dual power supply mode of solar energy and standby storage power supply for core water source and trunk pipeline monitoring points to reduce large-scale offline risks under extreme weather such as continuous heavy rain.

(2) Whole-life cycle standardized management of outdoor sensing equipment: Prioritize IP68 high anti-corrosion and waterproof industrial-grade terminals in subsequent equipment procurement; establish independent full-life cycle equipment archives to record installation time,

failure records and maintenance content. The business department collaborates with the operation and maintenance department to compile annual equipment renewal and replacement budgets in advance, predict aging failure risks through historical equipment data, and reduce monitoring blank periods caused by equipment damage.

(3) Deepen cross-system data fusion and big data analysis application: Optimize the platform big data analysis model, build regional water consumption load prediction models based on multi-year continuous flow and user water consumption data, and realize energy-saving optimized scheduling of urban water plants. Refine the classified statistical function of production-sales difference, accurately distinguish water loss sources including pipeline leakage, metering error and illegal water theft, and automatically generate integrated business analysis reports covering water quality safety, energy consumption statistics and revenue operation data.

(4) Hierarchical differentiated digital skill training system: Organize hands-on practical training on field terminal installation, commissioning and common fault troubleshooting for front-line maintenance teams; launch special training courses focusing on platform multi-dimensional data analysis and business performance statistics for business and dispatching management staff; establish long-term fixed technical support channels with equipment suppliers to realize rapid response and solution of software and hardware equipment faults.

6. Overall Comprehensive Operation Benefits of the Digital IoT Water Supply System

After the full stable operation of the whole-process IoT intelligent water supply platform, the project achieves remarkable comprehensive benefits in water resource conservation, enterprise operation cost control, drinking water safety guarantee and digital business management upgrading:

First, outstanding water-saving and cost-reducing economic benefits. Relying on DMA partition precise leakage control, the overall pipe network loss rate decreases year by year, reducing hundreds of thousands of tons of invalid water waste every year. Meanwhile, the consumption of water production medicaments, equipment power consumption and daily pipeline maintenance investment decline synchronously, effectively lifting the enterprise’s operating profit level.

Second, significant reduction of enterprise fixed labor input. The unattended digital transformation of mountain scattered pump stations and village water supply stations greatly cuts the frequency of manual long-distance patrol and the overall labor expenditure of the enterprise.

Third, comprehensive upgrading of urban and rural drinking water safety guarantee capacity. Water quality abnormal risks and pipeline hidden leakage faults shift from post-failure passive repair to pre-event active early warning, significantly improving emergency disposal efficiency during flood seasons and sudden water quality incidents. The system has maintained zero major water supply safety accidents for consecutive years.

Fourth, full realization of enterprise business digital transformation. Automatic remote meter reading, intelligent anti-theft water inspection and regional DMA partition performance assessment have been fully implemented. Real-time visualized business operation data greatly improves the efficiency of water fee recovery and daily water supply supervision, providing stable digital support for the long-term sustainable operation of urban-rural integrated water supply projects.

7. Conclusion

Traditional extensive manual operation and management modes are difficult to adapt to the high-quality development demands of mountain urban-rural integrated water supply, restricted by complex terrain, scattered pipe network layout and insufficient maintenance capacity. The whole-process IoT sensing technology, supported by full-node field perception, multi-mode remote data transmission and intelligent big data analysis, systematically solves multiple core management pain points of mountain water supply including full-process water quality supervision, accurate pipeline loss control, unattended operation of scattered rural water supply facilities and standardized user revenue management.

The practical operation experience of Wencheng County verifies that the construction of intelligent water supply IoT digital system is not a one-time simple equipment installation project. Long-term iterative optimization of communication network layout, outdoor equipment performance, big data mining application and compound talent training system is required according to the unique geographical and climatic characteristics of mountainous areas. In follow-up work, focusing on enterprise business operation optimization objectives, further deep mining of multi-dimensional value of IoT long-term monitoring data will be carried out to continuously optimize intelligent water supply dynamic scheduling models, improve scientific water loss assessment standards, reduce the comprehensive operation cost of rural mountain water supply facilities, and continuously explore the deep integration path of IoT, big data analysis and water supply service business, so as to provide replicable engineering practice reference for the sustainable high-quality development of county-level intelligent water supply in mountainous regions.

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

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