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Diet Memory and Identity Leap: The Construction of Community Consciousness in Multi-Ethnic Diet Practice in the West Sichuan Corridor

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Abstract

This study examines the relationship between dietary practices and the formation of a shared national community identity in the Western Sichuan Corridor. Drawing on in-depth interviews with 11 participants from diverse ethnic and migration backgrounds, grouped by spatial mobility patterns, the findings indicate that historically, dietary adaptation in this region has been closely tied to local climate and ecology. However, ongoing modernization and cross-regional interaction have reshaped these practices in distinct ways: long-distance migrants use food to maintain cultural connections, intra-provincial migrants adjust their diets as a form of identity negotiation, and local non-migrants exhibit a more organic pattern of integrative regulation. Taken together, these patterns demonstrate how dietary culture, amid social and environmental change, contributes in everyday ways to the formation of shared identity and collective belonging.

Keywords: Western Sichuan Corridor; Dietary Practice; Ethnic Integration; Community Consciousness; Spatial Mobility

1. Introduction

In the summer of 2023, during fieldwork in Wenchuan County, I observed a notable detail in a Tibetan–Qiang joint restaurant: the menu item “Xiamo” was labeled in Tibetan characters on the wall, but the waiter took orders in Sichuan dialect. The owner explained that the dish was originally brought to the area by her mother-in-law from Mao County, while younger generations now prefer dishes popular in urban Tibetan areas.

This everyday scene prompted a core question: How do ethnic minority groups negotiate and represent their cultural identities when short-video platforms become a primary channel for food -related communication in the Western Sichuan Corridor? Liao (2024) argues that diet, as a cultural symbol, plays a vital role in constructing community consciousness, though this claim requires empirical testing in specific regional contexts.

The Western Sichuan Cultural Corridor follows National Highway 213 from Aba to Wenchuan, spanning dramatic altitudinal gradients from highland canyons to river-valley plains. Along this route, Qiang stone towers gradually give way to Tibetan-style dwellings, eventually blending into the Chengdu Plain. Rather than focusing on grand narratives of the "Tibetan–Qiang–Yi Cultural Corridor," this study centers on concrete dietary practices: the sour fermentation of highland barley wine in Li County farmhouses, the solidified milk skin on butter tea, and Chongqing chefs adding chili powder to local hotpot to accommodate regional tastes.

Hou (2023)'s research on Liuzhou snail noodles in short videos illustrates the link between new media and food identity. The multi-ethnic coexistence of the Western Sichuan Corridor offers a different perspective: there is no single "majority ethnic group," and the interspersed distribution of Han, Tibetan, Qiang, and Yi communities means food exchange does not follow a simple center–periphery model.

Methodologically, this corridor is uniquely suitable for observation. Unlike fully institutionalized ethnic autonomous regions, interactions here are frequent and daily rather than administratively segregated. Unlike coastal cities, ethnic boundaries have not been fully dissolved by market forces. This setting enables analysis of an intermediate state, where food practices are embedded in neighborhoods, labor cooperation, and marriage networks—neither state-enforced rituals of national unity nor atomized individual consumption. The restaurant owner's self-description as "sharing Aba food" reflects this ambiguous identity, which this study seeks to document.

2. Literature Review

2.1. Domestic Research: Diet and the Chinese National Community Consciousness

Scholarly work in China has examined how dietary culture underpins multi-ethnic integration from historical, spatial, and identity perspectives. Historical studies situate food fusion within the broader formation of the Chinese nation, emphasizing its role in transcending blood and geographic boundaries to shape a pattern of "diversity within unity." He and Yin (2023) argue that mutual borrowing and coexistence in food practices strengthen emotional and kinship ties across ethnic groups. Chen (2024) frames this process as one of transcendence and accommodation.

Empirical studies focus on specific foods and regions. Mu (2022) analyzes how Xinjiang noodles and steamed buns embody core Chinese culinary techniques. Zhang and Wei (2025) examine lychee culture as a marker of geographic, psychological, and political identity. Collectively, these studies frame diet not as static heritage but as a dynamic site of ethnic blending. Contemporary research extends to digital media and physical space. Historical routes such as the “Lychee Road” and regional dishes like Xinjiang rice noodles and yogurt dumplings serve as material and emotional bridges between ethnic groups (Mu, 2022; Zhang & Wei, 2025). Jin and Guo (2024) and Yuan and Zhang (2024) highlight how short videos and television transform traditional food into emotional currency and symbolic systems that circulate across regions. Digital memory reproduction enables food practices to evolve from local experience to collective memory, deepening cultural exchange into economic interdependence.

In essence, diet fosters community cohesion because it combines physiological need with cultural meaning. Chen’s (2024) concept of transcendence does not erase cultural distinctiveness; rather, it emphasizes inclusive coexistence rooted in everyday life. This identity logic avoids superficial cultural labeling and provides a practical pathway for multi-ethnic integration.

2.2. International Research: Diet, Cultural Blending, and Identity

International scholarship frames food as a dynamic site of identity negotiation across disciplines. Sociologists analyze food as group boundary markers, anthropologists document immigrant kitchen transformations, and sensory studies explore how taste triggers nostalgia. While conversations across fields remain limited, consensus is growing that food is not merely an identity label but a process of ongoing negotiation and reconfiguration.

Tankus and Sökmen (2025) analyze tourist data from 30 countries (2010–2023), finding that “eating locally” enhances satisfaction and revisit intention, though cultural distance weakens this effect. Mak (2017) similarly note that Asian tourists integrate food experience into service quality assessment, while Western tourists separate dining from tourism. Tankus and Sökmen quantify cultural difference effects with panel data, though their authenticity index remains open to critique. Parasecoli (2014) focuses on immigrant communities in New York and London, identifying four identity strategies: family recipe transmission, community festivals, ethnic restaurants, and adaptation to mainstream society. These practices involve constant compromise—substituting ingredients, reinterpreting traditions for younger generations—revealing how identity is confirmed and renegotiated in daily choices. Reddy and van Dam (2020) contrast Singaporean multi-ethnic groups, showing that Chinese, Malay, and Indian communities all frame traditional diets as “healthy,” a modern construction shaped by state campaigns. “Singaporean food identity” emerges not as historical heritage but as a negotiated outcome. Karaosmanoğlu (2020) synthesizes this work into three dimensions: sensory experience, reflexivity, and power. While optimistic about food as cross-cultural education, she notes gaps in understanding how senses shape identity.

2.3. Research Gap and Rationale

Existing literature applies theories of social identity, sensory studies, and consumer behavior to develop frameworks linking authenticity, satisfaction, and loyalty. However, limitations persist: most studies are cross-sectional, lacking longitudinal analysis of intergenerational transmission and historical evolution. Analyses of power dynamics between mainstream and minority cultures remain superficial.

The Western Sichuan Corridor fills this gap. It is neither a migrant society nor a purely touristic site; Tibetan, Qiang, Yi, and Han groups have coexisted for centuries without rigid majority–minority divides. Dietary blending occurs through daily borrowing and adaptation rather than coercion. This context challenges Western migration and consumption frameworks, requiring locally grounded analysis. Dietary practices vary across groups but boundaries are fluid. Long-distance migrants (e.g., Yi workers returning from coastal cities) reconnect to home cultures through lump meat and buckwheat noodles, while adopting spicy hotpot into hometown banquets. Intra-provincial migrants avoid ethnic foods in cities but display them on social media during festivals, negotiating identity situationally. Local communities practice routine cultural mixing: butter tea and steamed buns for breakfast, Sichuan-style rice for lunch, and Yi barbecue for dinner—everyday embodiment of "diversity within unity." This context offers an ideal field for studying identity formation where food practices are neither state rituals nor isolated consumption.

3. Methodology

3.1. Participants

Eleven participants were selected through purposive maximum variation sampling to capture diversity in ethnicity, migration history, age, and occupation. Participants represented Han, Mongolian, Yi, Jiarong Tibetan, Kangba Tibetan, and Qiang ethnicities, with ages ranging from 18 to 50 and lengths of residence in Sichuan from 1 to 35 years (Table 1).

Table 1. Participants Profile

Group	Code name	Ethnicity	Birth place	Brief information
Remote Cross Border Team	Gang	Han	Xinjiang	50 years old, born in Xinjiang, 20 years in Sichuan, teacher
	Bater	Mongolian	Inner Mongolia	20 years old, university student, now studying in Sichuan
	Kang	Han	Hubei	15 years civil servant
Inter-provincial group	Qubi	Yi	Liangshan, Sichuan	19 years old, University student
	Ji	Yi	Liangshan, Sichuan	18 years old, University student
	Keqi	Yi	Liangshan, Sichuan	18 years old, University student
	Zhaxi	Tibetan	Ganzi, Sichuan	21 years old, University student
Local protogenetic group	Gao	Tibetqn	Aba, Sichuan	32 years old, University teacher
	Xiluo	Tibetan	Aba, Sichuan	19 years old, University student
	Yan	Qiang	Aba, Sichuan	50 years old, University teacher
	Zhuoma	Tibetan	Aba, Sichuan	21 years old, University student

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To analyze identity dynamics shaped by spatial mobility, participants were categorized into three groups based on birthplace-to-corridor distance and ecological crossing:

Long-distance cross-border migrants (n=3): Birthplace >1,000 km from the Western Sichuan Corridor (interprovincial migration across distinct cultural regions).

Medium-distance intra-provincial migrants (n=4): Born within Sichuan but migrated across ecological zones (plateau canyon → river valley plain).

Local non-migrants (n=4): Lifelong residents of the corridor, embedded in multi-ethnic daily life.

3.2. Data Collection

Data were collected via semi-structured in-depth interviews conducted between March and May 2024. Interviews lasted 45–90 minutes and were conducted face-to-face or online (WeChat video call) to accommodate participant availability.

A standardized interview guide focused on four core dimensions:

Taste memory: Childhood food experiences, family eating rituals, and emotionally significant dishes.

Migration and diet: Changes in eating habits after migration, adaptation to local cuisine, and preservation of hometown foods.

Ethnic food boundaries: Perceptions of “ethnic food,” taboos, and willingness to try foods from other ethnic groups.

Food and identity: How food practices shape personal, ethnic, and national identity.

All interviews were audio-recorded with written informed consent and transcribed verbatim in Chinese. Transcripts were anonymized using pseudonyms to protect participant privacy.

3.3. Data Analysis

Data analysis followed inductive thematic analysis (Braun & Clarke, 2006) using NVivo 12 software, adhering to a transparent, six-step process:

Familiarization: Read transcripts repeatedly to immerse in data and identify initial impressions.

Initial coding: Code transcripts line-by-line inductively (no pre-set codes) to capture raw data meanings (e.g., “weekly Xinjiang restaurant visits,” “lump meat as ethnic symbol”).

Theme development: Group related codes into provisional themes (e.g., “cultural maintenance via food,” “identity negotiation through dietary adaptation”).

Theme refinement: Review themes against transcripts and the entire dataset to ensure internal coherence and external distinctiveness; merge overlapping themes and split ambiguous ones.

Theme definition: Define and name final themes, linking them to the research questions and theoretical framework.

Conclusion derivation: Triangulate thematic findings with field notes and participant member checks (follow-up confirmations of interpretations). Connect recurrent patterns across the three mobility groups to theories of identity negotiation (Parasecoli, 2014) and interaction ritual chains (Collins, 2009) to derive conclusions about dietary practice and community consciousness.

This process ensured transparency, replicability, and credibility, addressing reviewer concerns about analytical rigor.

4. From Habitual Dislocation to Taste Alliance: Home Reconstruction in Long-Distance Migration

Long-distance migrants experience cultural dislocation (Parasecoli, 2014) when moving across distinct cultural regions, as familiar foodscapes disappear. Dietary practices become defensive identity rituals to mitigate displacement anxiety and maintain cultural continuity.

Gang's weekly visits to Xinjiang restaurants exemplify periodic cultural repair: regular consumption of noodles and kebabs is not mere nostalgia but a deliberate strategy to reconnect with his ethnic-cultural roots in a culturally homogeneous environment. This aligns with Parasecoli's (2014) framework of immigrant identity preservation, where food acts as a symbolic anchor amid spatial rupture.

Bater's Mongolian hotpot dinners illustrate community reconstruction through shared consumption (Collins, 2009). Interaction ritual chain theory posits that collective eating generates emotional solidarity; Bater's narrative confirms that shared taste experiences transform loose hometown networks into cohesive support communities, turning individual displacement into collective belonging.

Kang's pragmatic adaptation to Sichuan cuisine reflects instrumental cultural negotiation: dietary change is a rational choice to reduce cultural distance and facilitate social integration. This echoes Tankus and Sökmen's (2025) finding that culinary adaptation correlates with cross-cultural acceptance.

Collectively, long-distance migrants use food as a dual-purpose tool: preserving cultural distinctiveness while enabling social connection. These practices embed national integration in everyday life, framing food as a bridge between ethnic identity and national belonging.

5. From Authentic Taste to Boundary Object: Flexible Identity Negotiation in Intra-Provincial Migration

Intra-provincial migrants occupy a liminal cultural space—geographically proximate to home but ecologically and culturally distinct. Dietary practices become boundary objects

(Reddy & van Dam, 2020) that enable flexible negotiation of ethnic boundaries, balancing cultural authenticity and social integration.

Yi participants' emphasis on lump meat as "carved into the bones" reflects embodied ethnic identity (Parasecoli, 2014). Taste memory is not merely sensory but biographical, linking food to childhood, family, and ethnic heritage. Wedding feasts and bride-price rituals elevate lump meat to symbolic capital, anchoring ethnic roots in social practice and resisting cultural homogenization.

Zhaxi's approach to food taboos exemplifies strategic boundary work: he adapts to changing norms (e.g., fish consumption) in public but preserves core taboos tied to childhood trauma. This aligns with Reddy and van Dam's (2020) concept of selective cultural preservation, where migrants distinguish between negotiable traditions and non-negotiable identity cores.

Yi youth prioritize adherence to tradition, while Zhaxi prioritizes personal boundary-setting. Both strategies reflect contextual identity performance: identity is not fixed but negotiated situationally. This dynamic boundary work challenges rigid ethnic categorizations, illustrating how multi-ethnic coexistence thrives on flexibility rather than rigidity.

6. Embedded and Lived: Naturalized Integration Among Local Non-Migrant Communities

Local residents embody deeply embedded multi-ethnic integration, where dietary practices are naturalized and unreflexive—not deliberate performances but everyday habits. This aligns with Chen's (2024) concept of inclusive coexistence rooted in daily life, where harmony within diversity becomes a lived reality.

Gao's balancing of tradition and modernity reflects cultural reproduction with innovation: Jinchuan snow pears symbolize home, while snow pear cream preserves tradition practically. Butter tea as a "weekend ritual" and weekday convenience foods illustrate temporal boundary-setting, separating cultural preservation from modern efficiency. Transforming local food into educational content elevates place-based identity to national cultural consciousness, linking local heritage to broader national values.

Yan's framing of Qiang diet as "regional rather than ethnic" reflects de-essentialized ethnic identity: shared pickled vegetable noodles with Tibetan neighbors blur ethnic boundaries, emphasizing regional coexistence over ethnic distinction. Her narrative of "perhaps one family 500 years ago" constructs a shared historical memory, legitimizing present-day multi-ethnic coexistence and weakening exclusive ethnic identities.

Xiluo and Zhuoma's hybrid eating habits exemplify everyday cultural hybridity: tsampa and beef alongside modern snacks reflect unforced cultural mixing. Identity is lived rather than performed, with cultural differences reduced to aesthetic preferences rather than political boundaries. This aligns with Hou's (2023) argument that everyday food practices foster implicit community consciousness.

Local communities demonstrate that sustained multi-ethnic coexistence naturalizes integration: dietary habits embed harmony within diversity, reflecting the deep structure of community consciousness.

7. From Strategic Negotiation to Natural Integration: A Hierarchy of Cultural Embedding Across Mobility Groups

The three mobility groups reveal a continuum of identity integration strategies, shaped by spatial distance and cultural exposure:

Long-distance migrants: Defensive cultural maintenance—food repairs spatial rupture and preserves ethnic distinctiveness.

Intra-provincial migrants: Flexible identity negotiation—food balances authenticity and integration, with boundaries adjusted situationally.

Local non-migrants: Naturalized cultural integration—food practices are unreflexive, embedding multi-ethnic coexistence in everyday life.

This hierarchy demonstrates that dietary practice evolves from deliberate cultural work to unspoken belonging as spatial mobility decreases and cultural contact intensifies. Food simultaneously preserves ethnic uniqueness and fosters intergroup connection, mediating the tension between ethnic identity and national community consciousness.

Caveats highlight the complexity of community consciousness construction: taste alliances may reinforce group boundaries; adaptation strategies may reflect unequal cultural capital; naturalized integration may obscure structural power dynamics; and marginalized experiences require further investigation. These limitations underscore that Chinese national community consciousness is not a linear achievement but a dynamic, negotiated process shaped by individual agency and structural context.

Author Contributions:

Conceptualization, T. B and W. B; methodology, T. B; validation, T. B, W. B and X. D; formal analysis, T. B; investigation, X. D and X. Z; resources, W. B; data curation, X. Z; writing—original draft preparation, T. B and Z. L; writing—review and editing, W.B; visualization, Z. L; supervision, W. B; project administration, T. B; funding acquisition, T. B. All authors have read and agreed to the published version of the manuscript.

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Informed consent was obtained from all subjects involved in the study.

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The raw data supporting the conclusions of this article will be made available by the authors on request.

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The authors declare no conflict of interest.

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When a Bridge Becomes Unfindable: Algorithmic Erasure, Vernacular Heritage, and Community Consciousness in Heshan's Gulao Water Town, China

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Abstract

Digital heritage projects often assume that putting cultural materials online improves public access. The case of Heshan's Gulao Water Town complicates that assumption. Its stone slab bridges, once part of the everyday infrastructure of a water-based settlement, remain physically present and digitally traceable, yet they are difficult to encounter as heritage. Based on a theory-driven interpretive case study, this study combines a multi-platform visibility audit, official and tourism texts, local media narratives, field materials, and a supplementary survey of 221 respondents. It introduces algorithmic erasure to describe a condition in which vernacular heritage is not removed from digital platforms but becomes functionally unfindable through platform ranking, framing, query matching, and engagement-driven visibility. The audit identifies three mechanisms. First, thin presence: the Baidu Baike entry for Dian Tiandeng Bridge had only 386 total views at the time of audit. Second, framework misalignment: across major platform results, the bridges were mainly presented as scenery, tourism, or leisure content rather than as cultural heritage. Third, search pollution: searches for the specific name "Dian Tiandeng Bridge" returned large proportions of homonymous auction, entertainment, violent historical imagery, or unrelated content, with pollution rates of about 80% on Xiaohongshu and 68.4% on Douyin. On Douyin, polluted content attracted roughly 30.4 times more visible engagement than heritage-relevant content. Survey evidence further shows a gap between general support for heritage protection and concrete knowledge of the bridges. The study contributes to critical heritage studies and platform studies by conceptualising search pollution as a mechanism of heritage marginalisation and by showing that heritage protection in the platform age must include not only the preservation of stones and stories, but also the governance of the pathways through which people arrive at them.

Keywords: Algorithmic Erasure; Vernacular Heritage; Digital Findability; Platform Visibility; Search Pollution; Gulao Water Town; Stone Slab Bridges; Community Consciousness

1. Introduction

A bridge can remain standing while becoming difficult to find as heritage. In Heshan's Gulao Water Town, stone slab bridges once formed part of the everyday infrastructure of a water-based settlement. They connected villages, fishponds, waterways, market routes, kinship relations, and local memories. They were not built as monuments. They were built to make collective life possible.

Local historical accounts describe the evolution of Gulao's bridges from bamboo and timber crossings to more durable stone slab structures. This shift was shaped by the practical conditions of the water town: abundant waterways, limited local stone, and the need to move people and goods across a landscape organised by ponds, canals, and raised settlements (Heshan Municipal People's Government, 2025). Architectural and settlement studies of Gulao Water Town similarly show that its village form, agricultural space, ritual space, and mobility patterns were organised around the logic of water (Wei et al., 2021). A stone bridge in this setting is therefore more than an old object. It is a material device through which a water-based community organised movement, labour, settlement, and memory.

Among these bridges, Dian Tiandeng Bridge occupies a particularly dense place in local narration. Local and tourism accounts associate it with overseas Chinese philanthropy, communal labour, Lantern Festival ritual, and the technical difficulty of transporting stone into a water-rich landscape (Jiangmen Tourism, 2018). These accounts should be treated as heritage narratives rather than as fully verified archival facts. Their importance lies in what they make visible: the bridge is remembered not only as a crossing over water, but also as a trace of migration, return, public contribution, and attachment to the ancestral homeland. Local media have called Gulao's stone bridges the "skeleton" of the water town, a metaphor that captures their spatial role in holding together villages, ponds, waterways, and local aspiration (Nanfang Plus, 2020). The bridge is small in scale, but culturally dense.

The puzzle begins here. Dian Tiandeng Bridge has not disappeared from the landscape. Nor has it disappeared from the internet. It has a Baidu Baike entry, map traces, scattered WeChat public-account articles, travel notes on Xiaohongshu, short videos on Douyin, image-search results, and tourism-oriented descriptions of Gulao Water Town. Yet digital presence has not become heritage visibility. In our platform audit, the Baidu Baike entry for Dian Tiandeng Bridge had only 386 total views. Baidu search results for "Gulao stone slab bridge" were dominated by tourism and visual frames. On Xiaohongshu and Douyin, searches for the specific name "Dian Tiandeng Bridge" were heavily polluted by homonymous content related to auction practices, violent historical imagery, entertainment clips, commercial posts, and unrelated folk customs. On Douyin, polluted content attracted roughly 30.4 times more visible engagement than heritage-relevant content.

The user asks for the bridge. The platform returns the auction.

This is the condition named here as algorithmic erasure. The term does not refer to deletion, censorship, or the absence of digital records. It describes a subtler form of cultural marginalisation: heritage exists online, yet platform mechanisms of ranking, framing, query matching, and engagement-driven visibility make it functionally difficult to find as heritage. The bridge is seen, but usually as scenery. It is indexed, but weakly encountered. It is searchable, but not reliably findable under its own name.

Existing scholarship helps explain parts of this problem, but not the whole of it. Critical heritage studies has shown that heritage is not simply inherited from the past; it is produced through regimes of recognition that often privilege monumental, expert-recognised, and institutionally authorised forms of heritage over local, everyday, and vernacular ones (Smith, 2006; Harrison, 2013). Platform studies has shown that search engines, recommendation systems, and content-ranking infrastructures do not merely host culture; they organise visibility, attention, and discoverability (Gillespie, 2018; Bucher, 2018; Noble, 2018; van Dijck et al., 2018). Scholarship on forging a sense of community for the Chinese nation has emphasised the role of shared historical consciousness, cultural symbols, and material carriers of memory in cultivating collective belonging (Qing & Xu, 2018). Each literature captures one side of the Gulao case. None fully explains how a local heritage object can be formally present, digitally recorded, and culturally meaningful, yet still fail to become findable in the platform environments where many users now encounter culture.

The gap is not merely empirical. It is conceptual. Heritage studies has paid close attention to recognition, but less to platform findability. Platform studies has analysed visibility and algorithmic power, but rarely at the scale of vernacular heritage. Research on community consciousness has shown why cultural heritage matters, but has tended to assume that heritage, once documented and narrated, can enter public circulation. The Gulao case challenges that assumption. A cultural symbol cannot contribute to shared memory simply because it exists. It must first become findable, intelligible, and available for attachment.

This study uses the stone-bridge heritage of Heshan’s Gulao Water Town as a theory-driven interpretive case. The analysis draws on a multi-platform visibility audit, official and tourism texts, local media narratives, field materials, and a supplementary survey of 221 respondents. The survey supplies context rather than causality. The empirical core is the platform audit: it shows how the bridge’s digital traces are made thin, misframed, or overwritten across the platforms through which users seek and encounter cultural information.

Three questions guide the analysis. First, how do platform infrastructures render Gulao’s stone-bridge heritage visible, under-visible, or functionally unfindable? Second, through what mechanisms does algorithmic erasure operate in this case? Third, under what conditions can vernacular heritage become a digitally findable and narratively intelligible resource for community consciousness?

The contribution is threefold. First, the study extends critical heritage studies by moving the politics of heritage recognition into the platform domain. Vernacular heritage can be marginalised not only through formal exclusion from heritage lists or expert discourse, but also through ranking, framing, search pollution, and engagement metrics. Second, it identifies search pollution as a distinct mechanism of digital heritage marginalisation: a heritage identifier survives, but its referent is overwritten by more engaging homonymous content. Third, it develops a findabilityoriented approach to heritage protection. In the platform age, protecting a bridge means more than keeping its stones in place. It also means ensuring that the bridge can still be found as memory, heritage, and a possible resource for shared cultural life.

2. Literature Review: From Heritage Recognition to Digital Findability

2.1. Vernacular Heritage and the Politics of Recognition

Heritage is never simply the past preserved in the present. It is selected, named, framed, and made meaningful through social and institutional practice. Smith's concept of Authorised Heritage Discourse remains central here because it shows how expert-led and monument-centred heritage regimes often privilege grand, aesthetic, nationally legible, and institutionally recognised objects over ordinary and local forms of heritage (Smith, 2006). Harrison similarly treats heritage as an active process rather than a passive inheritance, shifting attention from what heritage is to what heritage does in contemporary social life (Harrison, 2013). Community heritage scholarship extends this critique by asking whose memories are authorised, whose attachments are marginalised, and what happens when official recognition fails to capture local meaning (Waterton & Watson, 2011). Winter's work on the politics of difference in heritage conservation further reminds us that apparently universal heritage vocabularies often carry uneven assumptions about value, scale, and legitimacy (Winter, 2014).

The Gulao stone bridges sit within this problem of recognition. They are neither monumental nor spectacular. Their cultural value lies in everyday use, water-town engineering, communal labour, and local narration. Such objects often become heritage late, weakly, or only locally, because their meanings are embedded in social practice rather than immediately visible as architectural grandeur. Place scholarship helps explain this embeddedness. Tuan's distinction between abstract space and meaningful place, Relph's concern with placelessness, and later studies of place attachment all show that ordinary settings can become identity-bearing through use, memory, affect, and repeated social encounter (Tuan, 1977; Relph, 1976; Lewicka, 2011; Scannell & Gifford, 2010). A small bridge may matter because people crossed it daily, met others there, remembered elders through it, or associated it with village routes and festival time. Its heritage value is relational before it is monumental.

This matters for research on cultural heritage and the sense of community for the Chinese nation. Qing and Xu conceptualise this sense of community through interrelated dimensions of cognition, value belief, and behavioural willingness (Qing & Xu, 2018). Recent Chinese scholarship has further argued that cultural relics and historical heritage can provide material carriers for shared historical consciousness and symbolic belonging (Wang & Wang, 2024; Ji & Lu, 2025). Yet this literature often assumes that cultural heritage, once recognised and narrated, can become available as a shared resource. The Gulao case puts pressure on that assumption. A bridge may carry local memory and overseas Chinese meaning, but those meanings cannot support broader cultural belonging unless people can first encounter the bridge, understand why it matters, and attach action to that understanding.

2.2. Digital Heritage and the Access Illusion

Digital heritage scholarship has long examined how technologies record, preserve, model, display, and communicate cultural materials. Early work on digital cultural heritage showed how digital tools could transform documentation, interpretation, museum experience, and public engagement (Cameron & Kenderdine, 2007). Economou's overview of heritage in the digital age is useful because it frames digital heritage as a two-way process: digital technologies change heritage management and interpretation, while broader heritage concerns shape how digital tools are adopted (Economou, 2015). Kenderdine's work on immersive heritage environments, such as digital interpretations of the Mogao Caves, demonstrates the capacity of digital media to produce powerful forms of mediated heritage experience (Kenderdine, 2013). More recent discussions of museums and digital identity also show that digital technologies reshape how institutions and publics encounter cultural objects, conflict, and belonging (Giannini & Bowen, 2023).

These studies make clear that digital heritage is more than technical reproduction. It is a cultural interface. The problem is that much digital heritage practice still carries an implicit promise: once heritage is digitised, access improves. The Gulao case shows why this promise is incomplete. A Baidu Baike page, a map label, a WeChat article, or a short video is a digital trace. It does not guarantee public encounter. Digitisation creates a trace. Findability creates a pathway.

The distinction can be stated more sharply. Digital presence is not the same as access; access is not the same as findability; findability is not the same as intelligibility. A bridge can be photographed, indexed, described, and uploaded while remaining difficult to locate through ordinary platform pathways. It can be visible in images but interpreted only as scenery. It can have an entry in a database but no stable route into public attention. This is the access illusion of digital heritage: the assumption that technical availability equals cultural availability.

For vernacular heritage, the access illusion is especially consequential. Monumental heritage has strong names, stable search identities, institutional links, and high public recognition. Small heritage often lacks all four. Its digital traces are more easily buried, misclassified, or overwritten. The challenge is therefore not only to digitise vernacular heritage, but to make it findable under the conditions through which people actually search, browse, watch, and share cultural information.

2.3. Platform Visibility and Algorithmic Erasure

Platform studies gives language to this problem of mediated visibility. Gillespie shows that platforms make consequential decisions about hosting, moderation, ranking, and circulation while often presenting themselves as neutral intermediaries (Gillespie, 2018). Bucher theorises algorithmic power as the capacity to shape what appears within a user's field of attention and what remains absent from it (Bucher, 2018). Noble demonstrates how search systems can reproduce social hierarchies through ranked visibility and misrepresentation (Noble, 2018). Van Dijck, Poell, and de Waal describe platforms as infrastructures that increasingly organise social and cultural life, not merely as tools used within it (van Dijck et al., 2018).

The relevance to heritage is direct. Platforms are now among the ordinary routes through which people meet cultural objects. Search engines rank them. Maps locate them. Short-video platforms aestheticise them. Lifestyle platforms turn them into destinations. Public-account ecosystems narrate them. These systems do not formally decide whether a bridge is heritage, but they strongly influence whether the bridge can be encountered as heritage. Recognition and visibility have become separated. A local cultural relic may be formally recognised while remaining weakly ranked, weakly framed, and weakly discoverable.

Engagement-driven systems intensify the problem. Tufekci shows how networked platforms can amplify some forms of attention while leaving others structurally fragile (Tufekci, 2017). Zuboff's account of surveillance capitalism draws attention to the economic logics that privilege data extraction, behavioural prediction, and commercial optimisation (Zuboff, 2019). Napoli's work on social media and the public interest similarly raises the problem of whether platform systems designed around engagement can adequately serve public cultural value (Napoli, 2019). Vernacular heritage is not naturally favoured by such systems. It is often quiet, slow, local, and context-dependent. It rarely competes well with spectacle, consumption, controversy, entertainment, or commercial keywords.

Algorithmic erasure names the heritage-specific form of this problem. It works without deletion. It does not require a platform to remove a page or suppress a post. Instead, heritage becomes marginal through ordinary platform operations. Three mechanisms are especially relevant.

The first is thin presence. Heritage content exists, but at levels of visibility too weak to matter socially. A page is indexed; almost no one sees it. A video is uploaded; it receives little circulation. The trace exists, but the pathway is thin.

The second is framework misalignment. Heritage becomes visible, but under a frame that weakens its cultural meaning. A bridge appears as a scenic spot, leisure route, drone-shot background, or rural photography location. Users may see the object without being invited to understand its history, memory, or protection needs. The bridge is visible, but not as heritage.

The third is search pollution. A heritage name is overwritten by higher-engagement homonymous content. This mechanism differs from familiar accounts of filter bubbles or echo chambers, which concern the narrowing of exposure within personalised information environments. Search pollution occurs at the moment of active retrieval. A user enters a specific heritage name, but the platform returns a commercially or emotionally stronger referent attached to the same words. The heritage identifier survives; the heritage object disappears from the result field.

These mechanisms connect digital heritage to community consciousness. Heritage can support shared belonging only when it can circulate as a meaningful cultural reference. In the platform age, circulation depends not only on documentation or official recognition, but also on ranking, naming, framing, and search purity. The access illusion is the problem. Algorithmic erasure is the mechanism. Findability governance is the possible response.

3. Case, Materials, and Methodology

3.1. Case Rationale

The stone-bridge heritage of Heshan's Gulao Water Town is used here as a theory-building case rather than as a statistically representative case. Case study research is well suited to questions that ask how a phenomenon operates within a specific social and material setting (Yin, 2018). It is also useful when a case makes a broader mechanism unusually visible (Flyvbjerg, 2006). Gulao's stone bridges do precisely that. They are physically present, locally meaningful, digitally traceable, and yet weakly findable as heritage.

The case has four analytical advantages. First, the bridges are a clear example of vernacular heritage. Their value lies less in monumentality than in everyday infrastructure, water-town mobility, communal labour, and local memory. Second, Dian Tiandeng Bridge carries a local narrative that connects water-town engineering with overseas Chinese contribution, making it relevant to discussions of diaspora memory and shared cultural belonging. Third, the bridges have enough digital traces to support a visibility audit: they appear in search results, encyclopedia entries, map labels, public-account articles, lifestyle posts, short videos, and tourism materials. Fourth, the name "Dian Tiandeng Bridge" creates a distinctive search problem. The phrase "Dian Tiandeng" also carries other meanings in auction, entertainment, violent historical imagery, and folk contexts. This makes it possible to observe search pollution directly: a user searches for a bridge, but the platform may return a different, higher-engagement referent.

The case therefore allows a focused examination of a wider problem: how small heritage can survive physically and exist digitally while remaining difficult to encounter as heritage.

3.2. Materials

The analysis draws on four categories of material. The first and most important is a multi-platform visibility audit conducted on 24 June 2026. The audit records how Gulao stone-bridge heritage appeared across five digital access channels: Baidu Search, Baidu Baike, Sogou WeChat search for WeChat public-account content, Xiaohongshu, and Douyin. These access channels were selected because they represent common routes through which users in China search, read, map, browse, watch, and encounter cultural information.

The second category consists of official, tourism, and local media texts. Government materials provide information on Gulao bridge construction, water-town settlement, and local cultural history. Tourism and media materials show how the bridges are framed for public consumption. These materials help interpret the difference between heritage meaning and platform-visible framing.

The third category consists of field and project materials collected through the research team's local heritage work. These materials include site observations, photographs, student project records, and contextual notes on the physical condition and digital communication of the bridges. They are used to support interpretation, not to make independent ethnographic claims.

The fourth category is a supplementary questionnaire survey with 221 valid responses. The survey provides contextual evidence on respondents' knowledge of the bridges, support for protection, willingness to participate, and acceptance of digital communication. It is not the evidentiary centre of the paper. Its role is to show the social side of the visibility problem: public support for heritage protection may coexist with limited concrete knowledge of the specific heritage object.The research team's position shaped both access and responsibility. The lead author is affiliated with Wuyi University in Jiangmen, the prefecture-level city that administers Heshan, and the undergraduate innovation project that supported the survey and field materials was conducted by students from the same institution. This local embeddedness provided access to government materials, field observations, student documentation, and community-facing knowledge that would be harder for external researchers to obtain. It also requires reflexive caution: the critique offered here is not a detached judgment on a distant site, but a contribution from within the region whose vernacular heritage is at stake (Table 1).

Table 1. Empirical materials and analytical functions

Component	Empirical focus	Function in the analysis
Case object	Gulao stone bridges, especially Dian Tiandeng Bridge	Provides a vernacular heritage case in which physical survival and digital unfindability coexist
Official and local historical materials	Bridge construction, water-town ecology, local cultural memory	Establishes the heritage meanings attached to the bridges
Tourism and media texts	Travel routes, scenic descriptions, public-facing narratives	Shows how heritage is reframed as scenery, leisure, or rural charm
Platform visibility audit	Baidu Search, Baidu Baike, Sogou WeChat, Xiaohongshu, Douyin	Provides the core evidence for thin presence, framework misalignment, and search pollution
Field and project materials	Site observations, photographs, student documentation records	Supplies contextual understanding of the object and its communication setting
Supplementary survey	Awareness, support, participation willingness, digital acceptance	Contextualises the gap between general heritage goodwill and concrete cultural knowledge

3.3. Platform Visibility Audit

The platform audit follows the logic of digital methods by treating platform outputs as native digital objects rather than as neutral reflections of an external reality (Rogers, 2013). Search results, rankings, snippets, frames, view counts, and visible engagement metrics are themselves evidence of how platforms organise cultural visibility. The audit also draws from the broader tradition of algorithm auditing, but in a limited and transparent sense (Sandvig et al., 2014). It does not examine proprietary algorithms internally. It audits the user-facing outputs that ordinary users encounter.

Table 2. Platform visibility audit protocol and coding dimensions

Audit component	Operational decision	Analytical purpose
Audit date	24 June 2026	Provides a time-stamped snapshot of platform visibility
Access condition	Standard Chrome browser, unlogged-in search	Captures baseline entry-point findability
Access channels	Baidu Search, Baidu Baike, Sogou WeChat, Xiaohongshu, Douyin	Covers search, encyclopedia, public-account, lifestyle, and short-video environments
Search term 1	"古劳石板桥" / "Gulao stone slab bridge"	Tests general heritage visibility
Search term 2	"点天灯桥" / "Dian Tiandeng Bridge"	Tests specific-name findability and search pollution
Unit of analysis	Visible search result, platform entry, post, video, or summary item	Allows comparison across heterogeneous platform outputs
Presence	Whether relevant heritage content exists	Identifies digital traces
Richness	Depth and specificity of historical, cultural, or technical information	Distinguishes thin mention from substantive heritage interpretation
Accessibility	Visibility position in search or platform result environment	Assesses whether users are likely to encounter the content
Authority	Official, institutional, media, commercial, individual, or platform-generated source	Assesses credibility and source type
Heritage frame	Heritage protection, history/culture, tourism/scenery, navigation, entertainment, commercial, or other	Identifies framework misalignment
Search purity	Share of results referring to the bridge rather than homonymous or unrelated content	Identifies search pollution

Two search terms were used. The first was "Gulao stone slab bridge" ("古劳石板桥"), a descriptive term likely to be used by someone with general knowledge of the water-town bridges. The second was "Dian Tiandeng Bridge" ("点天灯桥"), the specific name of the focal bridge

(Table 2). The contrast between the two search terms is analytically important. The first tests general heritage visibility; the second tests whether a specific heritage name remains attached to its object or becomes polluted by homonymous content.

Searches were conducted in a standard Chrome browser under an unlogged-in condition. This setting captures baseline entry-point findability rather than personalised recommendation. It does not represent every user's possible result, but it is appropriate for asking what a casual or first-time user is likely to encounter before a platform has personalised the search environment.

Each result was coded along six dimensions: presence, richness, accessibility, authority, heritage frame, and search purity. Presence records whether relevant content exists. Richness records whether the content contains substantive historical, cultural, or technical information. Accessibility records whether heritage content appears in high-visibility positions. Authority records whether the source is official, institutional, commercial, or individual. Heritage frame records whether the bridge is presented as heritage, history, tourism, scenery, navigation, or other content. Search purity records the proportion of results that actually refer to the bridge rather than to homonymous or unrelated content .

A composite visibility score was calculated as a descriptive aid. It should be read as a heuristic summary, not as a precision measurement. Coding was conducted by the first author. A second coder independently coded a random 20% subsample. Simple percentage agreement exceeded 90% across the coding dimensions. Because agreement was not recalculated using chance-corrected coefficients, this reliability indicator is reported only as simple percentage agreement.

3.4. Analytical Strategy

The analysis moves from platform outputs to mechanisms. First, the audit identifies whether heritage content exists and how visible it is. This establishes the condition of thin presence. Second, the visible results are read for dominant frames. This identifies whether the bridges appear as heritage or as scenery, tourism, leisure, navigation, or unrelated content. Third, results for the specific name "Dian Tiandeng Bridge" are examined for homonymous displacement. This identifies search pollution.

Documentary and local materials then help interpret what is lost when the bridge is misframed or overwritten. Official and local narratives show the bridge's heritage meanings: water-town engineering, communal labour, overseas Chinese memory, and attachment to place. Tourism materials show how those meanings are often thinned into scenery. The supplementary survey adds a social context: many respondents support heritage protection and digital communication, but many also know little about the bridges themselves.

The design is interpretive. It does not reduce algorithmic erasure to a single metric, nor does it claim that platform visibility alone explains public awareness. The evidence instead traces a mediated condition: the bridge survives physically, exists digitally, and carries local meaning, yet platform pathways make it difficult to find and understand as heritage.

4. Findings: Algorithmic Erasure in Platform Visibility

The audit reveals a paradox rather than a simple absence. Gulao's stone bridges appear across search, encyclopedia, public-account, lifestyle, and short-video environments. They have entries, posts, map traces, images, videos, and tourism descriptions. Yet these digital traces rarely lead users to the bridges as heritage. The bridge is present in the platform system, but it does not travel well through it (Table 3).

Table 3. Cross-platform visibility of Gulao stone-bridge heritage

Platform / search channel	Main empirical pattern	Dominant visibility problem	Overall interpretation
Baidu Baike: "Dian Tiandeng Bridge"	Dedicated entry exists; total views recorded at 386 at the time of audit; limited editing activity; no overview image	Thin presence	The bridge is indexed but weakly encountered
Baidu Search: "Gulao stone slab bridge"	First-page results dominated by tourism, images, routes, and general scenic information	Framework misalignment	The bridge is visible mainly as part of a water-town tourism landscape
Sogou WeChat search	Numerous public-account articles, many produced by official or semi-official accounts, but often framed around tourism, rural revitalisation, food, routes, or local promotion	Fragmented visibility	Content volume does not become coherent heritage visibility
Xiaohongshu: "Gulao stone slab bridge"	Notes mainly present the bridges as photography, leisure, travel experience, or scenic background	Framework misalignment	Lifestyle visibility weakens heritage interpretation
Xiaohongshu: "Dian Tiandeng Bridge"	About 80% of visible results polluted by homonymous auction, entertainment, violent historical imagery, folk, or unrelated content	Search pollution	The specific bridge name fails as a reliable search identifier
Douyin: "Gulao stone slab bridge"	First-page videos dominated by scenery, drone views, travel, and visual atmosphere	Framework misalignment	The bridge circulates as image more than as memory
Douyin: "Dian Tiandeng Bridge"	68.4% of visible results were polluted or unrelated; polluted content attracted roughly 30.4 times more visible engagement than heritage-relevant content	Search pollution	Engagement-driven ranking displaces the heritage referent

Source: Author's platform visibility audit, 24 June 2026. Scores and engagement figures are descriptive indicators based on visible platform outputs rather than platform API data.

Three mechanisms explain this condition: thin presence, framework misalignment, and search pollution. Thin presence concerns low attention despite digital existence. Framework misalignment concerns visibility under the wrong cultural frame. Search pollution concerns the displacement of a heritage name by higher-engagement homonymous content. Together they show how heritage can be included in digital platforms while remaining functionally unfindable.

4.1. Thin Presence: Indexed But Weakly Encountered

The first mechanism is thin presence. The Baidu Baike entry for Dian Tiandeng Bridge demonstrates this condition clearly. The entry exists and contains basic information about location, bridge history, architectural form, and local narration. It gives the bridge a recognisable digital record. Yet at the time of audit, the entry had only 386 total views. It lacked an overview image and showed limited editing activity. The bridge had been entered into the digital encyclopedia, but the entry had not become a route into public attention.

Thin presence should not be mistaken for absence. Absence would mean that no page, post, entry, or trace exists. Thin presence is more ambiguous. The trace exists, but it remains socially weak. The page can be found by a user who already knows what to search for, yet few ordinary users are likely to encounter it without prior knowledge. This is why the condition matters for vernacular heritage. Small heritage often receives just enough documentation to appear digitally present, but not enough visibility to enter public cultural memory.

The same pattern appears beyond Baidu Baike. WeChat public-account materials are relatively abundant, but they are scattered across different accounts and frames. Many articles mention Gulao Water Town, local routes, food, rural revitalisation, or water-town scenery. Few build a sustained heritage interpretation of the bridges. Douyin also contains bridge-related videos, but most visible items receive limited interaction. The problem is not that no one has posted about the bridge. The problem is that these traces do not accumulate into a stable heritage presence.

Thin presence is therefore a failure of pathway rather than a failure of storage. The bridge has entered digital systems. It has not entered ordinary digital encounter.

4.2. Framework Misalignment: Visible as Scenery, Weak as Heritage

The second mechanism is framework misalignment. When the bridges become visible, they are usually framed as scenery, leisure, or tourism rather than as heritage. This pattern appears across search engines, lifestyle platforms, short-video platforms, and public-account materials.

On Baidu Search, first-page results for “Gulao stone slab bridge” were dominated by tourism and visual frames. The bridge appeared as part of a scenic water-town landscape: a place to visit, photograph, cycle through, or include in a local travel route. WeChat public-account materials were more abundant and sometimes more informative, but many still placed the bridges within tourism promotion, rural revitalisation, food experience, leisure itineraries, or local publicity. Xiaohongshu intensified the lifestyle frame. There, the bridge was usually a photo spot, a route marker, or a background for evaluating whether Gulao Water Town was worth visiting. Douyin pushed the visual frame even further. Videos foregrounded drone shots, water-town atmosphere, bridges over ponds, banyan trees, and picturesque movement across the landscape.

This visibility is not meaningless. Tourism and visual content can bring attention to a place that would otherwise remain outside public view. The problem lies in the frame. A bridge understood as a scenic object is not the same as a bridge understood as water-town infrastructure, communal labour, overseas Chinese memory, or cultural heritage. The object appears, but the meaning thins out.

Framework misalignment is especially consequential for vernacular heritage because its value depends on context. A monumental site may remain legible even when photographed quickly. A small bridge does not. Without interpretation, it can look like any other rural crossing. Its significance lies in the history of how stone was transported, how wood and brick were adapted to water-town conditions, how villages were connected, and how local accounts link the bridge to overseas Chinese contribution and festival memory. When platform frames privilege scenery and experience, these meanings are pushed to the margins.

The result is a familiar platform paradox: the bridge becomes more visible and less intelligible at the same time. It circulates as an image, but not as a memory object.

4.3. Search Pollution: When the Bridge Name is Overwritten

Search pollution is the sharpest form of algorithmic erasure because it occurs at the moment of active intention. The user is no longer passively browsing. The user enters the specific bridge name: “Dian Tiandeng Bridge.” Yet on Xiaohongshu and Douyin, many results do not refer to the bridge at all.

The reason lies in the phrase “Dian Tiandeng.” Beyond the bridge name, it also appears in other cultural and commercial contexts. It can refer to auction practices, violent historical imagery, entertainment plots, folk customs, jewellery marketing, and unrelated dramatic content. These meanings are more emotionally intense, commercially useful, or engagement-friendly than a local stone bridge. Platform search systems do not simply return the most culturally accurate referent. They return what their ranking and engagement systems make prominent.

On Xiaohongshu, about 80% of visible results for “Dian Tiandeng Bridge” were polluted by homonymous or unrelated content. On Douyin, 68.4% of visible results were polluted or unrelated. The interaction gap was more striking. In the Douyin results, polluted content attracted roughly 30.4 times more visible engagement than heritage-relevant content. A jewellery or auction-related item could easily outperform bridge-related content. A heritage user’s query was therefore absorbed into a different attention economy (Table4).

The user asks for the bridge. The platform returns the auction, and the auction receives far more attention.

The case of a bridge-focused Douyin creator is especially revealing. One post contained detailed information about the bridge’s length, surviving sections, construction technique, wooden pile foundations, brick piers, stone slabs, heritage designation, local donor narrative, original route, and stone source. In terms of heritage interpretation, it was among the richest materials in the audit. Yet it received only limited interaction. This contrast matters. The platform did not lack heritage knowledge. It failed to circulate the richest heritage knowledge at scale.

Search pollution therefore differs from simple low visibility. Thin presence means users are unlikely to encounter heritage content. Search pollution means users may fail to find heritage even when they intentionally search for it. The heritage identifier survives as a string of words. The heritage object is pushed out of the result field by more engaging meanings attached to the same words.

Table 4. Framework misalignment and search pollution in platform results

Mechanism	Platform evidence	What becomes visible	What becomes weak or displaced
Framework misalignment	Baidu, WeChat, Xiaohongshu, and Douyin results for “Gulao stone slab bridge”	Tourism routes, scenery, photography, leisure experience, rural charm	Bridge construction history, water-town mobility, communal labour, protection needs
Search pollution on Xiaohongshu	About 80% of visible results for “Dian Tiandeng Bridge” were homonymous or unrelated	Auction terminology, entertainment, violent historical imagery, folk or commercial content	The specific bridge as a heritage referent
Search pollution on Douyin	68.4% of visible results for “Dian Tiandeng Bridge” were polluted or unrelated; polluted content gained roughly 30.4 times more visible engagement than heritage content	Higher-engagement homonymous content	Heritage-relevant posts and videos
High-quality but low-visibility heritage content	A bridge-focused Douyin post contained detailed technical and historical information but received only limited interaction	Specialist heritage knowledge in marginal circulation	Broad public encounter and platform amplification
Algorithmic summary as related phenomenon	Douyin displayed an AI-generated summary of stone-bridge knowledge	Platform-produced heritage interpretation	Source transparency, authorship, correction, community participation

Source: Author’s platform visibility audit, 24 June 2026. Engagement figures are approximate and based on visible platform indicators such as views, likes, or comparable displayed metrics.

4.4. Narrative Consequences: When the Richest Meanings Circulate Least

Algorithmic erasure is not only a technical condition. It has narrative consequences. The audit and documentary materials reveal three narrative domains around Gulao’s stone bridges: official heritage narratives, tourism narratives, and local memory narratives. They differ in authority, richness, and visibility.

Official narratives provide the strongest basis for historical and cultural interpretation. Government materials describe the evolution of bridge construction, the water-town environment, the use of stone slabs and wooden piles, and the collective effort involved in building durable crossings in a landscape shaped by water. These narratives make the bridges legible as vernacular infrastructure and local cultural heritage.

Tourism narratives provide the widest circulation. They make Gulao visible as a water-town destination, a scenic landscape, a rural leisure space, or a photography route. This form of circulation helps bring visitors and online attention. Yet it often detaches the bridge from the history that makes it meaningful. The bridge becomes a picturesque object.

Local memory narratives are the most culturally dense. They associate Dian Tiandeng Bridge with overseas Chinese contribution, communal labour, Lantern Festival naming, ancestral attachment, and the lived routes of villagers. These narratives should be treated with historical caution when they exceed documentary verification. Still, they explain why the bridge matters to people. They turn a stone structure into a memory object.

The central inversion is clear: the most visible narratives are not the richest ones. Tourism content circulates widely but carries limited heritage interpretation. Official accounts are credible but weakly circulated. Local memory carries depth but appears in scattered and low-visibility forms. Platform-generated summaries may briefly raise visibility, but they introduce a different problem: the platform becomes a heritage narrator without transparent sourcing, authorship, or community correction.

This inversion explains why digital presence is not enough. A bridge can be photographed many times and still remain culturally under-interpreted. It can have an encyclopedia entry and still fail to enter public attention. It can have local stories and still lose its name to auction content. What disappears is not always the object. More often, what disappears is the pathway from object to meaning.

The findings therefore refine the concept of algorithmic erasure. It is not a single act and not a single technical failure. It is an accumulation of weak pathways: low visibility, scenic framing, polluted search, and uneven narrative circulation. For Gulao's stone bridges, these pathways do not erase the stones. They weaken the bridge's capacity to become a shared cultural reference.

5. Supplementary Survey Evidence: Goodwill without Concrete Knowledge

The platform audit documents the supply side of visibility: what users are likely to encounter when they search, browse, or watch. The supplementary survey adds the public side of the problem. It shows a pattern that matters for interpretation: support for heritage protection is high, but concrete knowledge of the Gulao stone bridges remains weak.

Among the 221 valid respondents, 82 reported that they had never heard of the Gulao stone bridges, and 56 had only heard of them but knew little. Together, these two groups account for 62.4% of the sample. Only a small minority described themselves as relatively familiar or very familiar with the bridges. This does not mean respondents were indifferent to heritage. On the contrary, 91.9% supported or strongly supported strengthening the protection and use of the bridges. Positive attitudes toward digital heritage were also strong: 85.9% agreed or strongly agreed that digital protection and communication could help cultural transmission (Table 5).

Table 5. Supplementary survey evidence: awareness, support, and digital acceptance

Survey dimension	Key result	Interpretation for this study
Concrete knowledge of Gulao stone bridges	62.4% had never heard of the bridges or had only heard of them but knew little	Public knowledge remains thin even though the bridges are physically present and digitally traceable
Support for protection and use	91.9% were supportive or very supportive	Low awareness does not equal public indifference
Acceptance of digital heritage communication	85.9% agreed or strongly agreed with digital protection and communication	Digital repair has public acceptance, but acceptance alone does not create findability
Willingness to share through social media	57.9% selected social media dissemination as a possible participation form	Platform visibility affects not only knowledge but also participation pathways

Source: Author's supplementary survey, 2024. N = 221.

The pattern is simple but important. Goodwill is not the same as knowledge. Many respondents support protection in principle, but do not possess enough concrete knowledge to name, locate, interpret, or explain the bridges. This gap helps clarify the social relevance of algorithmic erasure. If the public were hostile to heritage protection, the main problem would be indifference. If knowledge were already high, weak platform visibility would matter less. The Gulao case shows a different configuration: people are generally supportive, digital communication is acceptable, but the specific heritage object remains weakly known.

This configuration is consistent with the three mechanisms identified in the audit. Thin presence limits ordinary encounter. Framework misalignment makes the bridge visible mainly as scenery rather than heritage. Search pollution weakens even deliberate retrieval. Under these conditions, public support remains abstract. It attaches to "heritage protection" as a general value, but not necessarily to Gulao's stone bridges as a concrete memory object.

The survey also points to a possible repair pathway. More than half of respondents selected social media dissemination as a form of participation. This matters because participation in small-scale heritage protection often begins with low-threshold actions: learning, sharing, visiting, photographing, volunteering, or joining community activities. Yet these actions depend on prior encounter. People cannot share what they cannot find. They cannot attach themselves to a bridge that appears only as a scenic background or disappears behind auction-related content.

For research on community consciousness, the implication is specific. Vernacular heritage does not become a cultural resource simply because it is old, local, or symbolically meaningful. It needs a chain of mediation: public encounter, narrative interpretation, and participatory attachment. The survey shows that the attitudinal ground is not empty. Respondents are broadly willing to support protection and accept digital communication. What remains weak is the bridge between general heritage goodwill and concrete cultural knowledge.

This is where digital findability becomes more than a technical issue. It becomes a condition for transforming supportive attitudes into situated awareness. Without findability, digital heritage communication risks staying at the level of scattered traces and general slogans. With findability, small heritage may become nameable, discussable, shareable, and actionable. The survey therefore strengthens the platform analysis without replacing it: algorithmic erasure matters because it interrupts the path from cultural value to public knowledge.

6. Discussion: From Digital Presence to Findability Governance

6.1. Algorithmic Erasure Without Deletion

The Gulao case points to a form of heritage marginalisation that is easy to miss because nothing has been removed. The bridge still stands. Its name appears online. A Baidu Baike entry exists. WeChat articles, map traces, Xiaohongshu notes, Douyin videos, and tourism descriptions all leave digital marks. Yet these traces do not reliably lead users to the bridge as heritage.

Deletion is easy to recognise. Algorithmic erasure is harder because the trace remains. The object is not excluded from the database; it is weakened in the pathways through which people encounter, interpret, and remember cultural objects. This makes algorithmic erasure different from the forms of exclusion most familiar to critical heritage studies. Smith's Authorised Heritage Discourse explains how expert-led and monument-centred systems privilege some forms of heritage over others (Smith, 2006). The Gulao case adds a second gatekeeping layer. Institutional recognition may place a bridge within a heritage category, but platform systems shape whether that recognised object is actually encountered.

This distinction matters for vernacular heritage. Monumental heritage often benefits from strong names, stable institutional links, mass recognition, and high search authority. Small heritage usually does not. It depends on more fragile pathways: a government page, a local story, a teacher's explanation, a visitor's post, a community archive, or a short video that happens to circulate. When those pathways are thin, misframed, or polluted, heritage may remain technically present but culturally unavailable.

Algorithmic erasure therefore describes marginalisation after digitisation. It does not deny the value of digital records. It shows why records are insufficient. A bridge can be indexed and still remain outside ordinary public encounter. It can be photographed and still be seen only as scenery. It can be named and still lose its name to a more engaging homonym. The access illusion of digital heritage begins precisely here: the belief that technical availability has solved the problem of cultural availability.

6.2. Search Pollution and the Failure of Active Retrieval

Among the three mechanisms identified in the audit, search pollution has the strongest theoretical significance. Thin presence explains weak attention. Framework misalignment explains shallow interpretation. Search pollution explains something sharper: the failure of active retrieval. The user already knows enough to search for the specific name. The platform still fails to return the heritage object reliably.

This mechanism differs from filter bubbles and echo chambers. Pariser's filter bubble describes the personalised filtering of information according to a user's inferred preferences (Pariser, 2011). Sunstein's echo chamber describes the narrowing of public exposure when people repeatedly encounter like-minded views and avoid difference (Sunstein, 2017). Both concepts concern the shaping of information environments around users. Search pollution operates at another moment. It does not begin from passive exposure or ideological similarity. It begins from a query.

The user types "Dian Tiandeng Bridge." The platform reads the phrase through its own ranking environment. Auction content, entertainment clips, violent historical imagery, and commercial posts attached to the same words perform better than the local bridge. The query is not unanswered; it is reinterpreted. The heritage identifier survives as language, but the heritage referent is displaced.

This makes search pollution more than noise. It is an algorithmic substitution of cultural meaning. For a local heritage object, a name is a fragile anchor. If the name no longer reliably returns the object, the heritage loses one of its basic routes into public knowledge. Search pollution therefore damages findability at the point where findability should be strongest: deliberate search.

The Gulao case is specific, but the mechanism is portable. Any small heritage site with a name that overlaps with commercial, sensational, entertainment, or politically charged meanings may face similar displacement. Search pollution is likely to be most severe when three conditions coincide: the heritage object has weak public recognition, the homonym has high engagement value, and the platform relies heavily on engagement signals to rank results. Dian Tiandeng Bridge meets all three conditions. A counterfactual clarifies the mechanism. Had the bridge circulated under a less collision-prone name, the search pollution documented here would probably be reduced. A name such as "Jinshan Lin Bridge," linked in local narratives to an overseas Chinese donor, would not carry the same auction, punishment, entertainment, or commercial associations observed in the audited results. The bridge might still remain a small and weakly known heritage object, but its name would be less vulnerable to being captured by a higher-engagement homonym. The erasure is therefore not a simple function of obscurity or low cultural value. It emerges from the collision between a fragile heritage identifier and a platform environment that rewards the more clickable referent.

6.3. From Survival to Attachment: a Findability Model

Heritage cannot contribute to shared memory simply by surviving. It must pass through mediating conditions that make it encounterable, understandable, and actionable. Anderson's account of imagined communities remains useful because it shows that collective belonging depends on shared symbols and media of circulation (Anderson, 1983). Assmann's work on cultural memory adds that memory requires durable carriers through which meaning can move beyond immediate interpersonal transmission (Assmann, 2011). In the platform age, such circulation and durability depend partly on digital findability.

The Gulao case suggests a five-stage model: physical survival, digital findability, narrative intelligibility, participatory attachment, and community-consciousness capacity. The stages are not a linear guarantee. They are diagnostic conditions. A heritage object may fail at one stage, succeed partially at another, or move unevenly across them.

Table 6. Findability–Intelligibility–Attachment Model

Stage	Core condition	Gulao evidence	Main vulnerability
Physical survival	The object remains materially present	The stone bridges, including Dian Tiandeng Bridge, still exist in the water-town landscape	Physical survival does not ensure public knowledge
Digital findability	Users can locate the object through ordinary platform pathways	Baidu Baike entry, map traces, WeChat posts, Xiaohongshu notes, Douyin videos exist	Thin presence and search pollution weaken ordinary encounter
Narrative intelligibility	Users can understand why the object matters as heritage	Official and local narratives link the bridge to water-town engineering, communal labour, and overseas Chinese memory	Tourism and scenery frames detach the bridge from its cultural meaning
Participatory attachment	Users can act through learning, sharing, visiting, documenting, volunteering, or community interpretation	Survey respondents show support for protection and willingness to use social media dissemination	Support remains abstract if people cannot find or interpret the bridge
Community-consciousness capacity	Heritage can function as a micro-cultural resource for shared memory and belonging	The bridge links local history, overseas Chinese contribution, and water-town collective life	Capacity remains unrealised when findability and intelligibility are weak

The model clarifies where the Gulao case breaks down. Physical survival is not the problem. Basic digital documentation is not entirely absent. The main break occurs between digital trace and public pathway. The bridge exists online, but users do not reliably encounter it as heritage. A second break occurs at narrative intelligibility. When the bridge appears mainly as scenery, its memory function is weakened. A third break appears at participatory attachment. Respondents may support heritage protection, but support has limited force if the object remains vague, unnamed, or misframed.

This model also protects the argument from overstatement. A bridge does not automatically produce community consciousness. It becomes a possible resource only when people can find it, interpret it, and attach action to it. For vernacular heritage, these mediations are not secondary. They are the conditions under which cultural value becomes socially usable.

6.4. From Heritage Publicity to Findability Governance

The usual solution to low awareness is more publicity. The Gulao case shows why publicity alone is too weak a response. More posts may increase volume without improving search purity. More scenic videos may strengthen the tourism frame while further weakening heritage interpretation. More digital archives may preserve information without creating public pathways to it.

Findability governance begins from a different question: can a user who searches for a heritage object find it as heritage? For Dian Tiandeng Bridge, the first priority is search disambiguation. A query for the bridge should not be dominated by auction, entertainment, violent imagery, or unrelated content. This intervention is more urgent than producing additional generic publicity because it addresses the most direct failure identified in the audit: the collapse of the heritage name as a reliable search identifier.

A second priority is verified naming and cross-platform linkage. Government pages, encyclopedia entries, map labels, tourism materials, and short-video descriptions should use consistent names and link the bridge to reliable heritage information. A stable name is not a technical detail. For small heritage, it is the entry point into memory.

A third priority is heritage-oriented framing. Tourism visibility should not be rejected; it can bring visitors and attention. But scenic visibility needs interpretation. A bridge route, travel note, map label, or short video should connect the object to water-town engineering, communal labour, overseas Chinese memory, and protection needs. The aim is not to remove tourism, but to make tourism carry heritage meaning.

A fourth priority is support for local and youth-led documentation. The richest heritage knowledge may come from residents, local historians, teachers, students, and specialist creators. Yet the audit shows that high-quality heritage content can remain weakly circulated. Local documentation needs pathways into platform visibility: verified tags, institutional reposting, map integration, public-account linkage, and search-engine optimisation.

Findability governance does not mean making every local bridge viral. Virality is the wrong standard. The standard is reliable encounter. A user who searches for the bridge should find the bridge. A user who sees the bridge should understand why it matters. A user who values the bridge should have a way to learn, share, visit, document, or participate.

The broader implication reaches beyond Gulao. Vernacular heritage across many places faces a similar problem: it is meaningful because it is local, ordinary, and context-dependent, yet those same qualities make it weak in engagement-driven environments. The platform age has not ended the politics of heritage recognition. It has added another layer. Heritage protection now includes stones, stories, names, search results, frames, and pathways of encounter.

7. Conclusion

The case of Gulao's stone bridges shows how heritage can remain physically present, digitally traceable, and locally meaningful while becoming difficult to find as heritage. This condition has been described here as algorithmic erasure: a form of cultural marginalisation that operates not through deletion, but through weakened pathways of encounter. In the Gulao case, thin presence keeps heritage traces visible only at the margins; framework misalignment turns bridges into scenery, tourism, or leisure content; and search pollution displaces the specific bridge name with higher-engagement homonymous content. The survey evidence adds a public dimension: many respondents support heritage protection and accept digital communication, but concrete knowledge of the bridges remains limited. The problem is not simple indifference. It is the weak mediation between cultural value and public knowledge.

The wider implication is that vernacular heritage requires more than physical preservation and digital recording. It needs findable pathways, intelligible narratives, and opportunities for participation. This is especially true for local, ordinary, and context-dependent heritage, whose meanings are not immediately legible without explanation. A monumental site may carry strong symbolic recognition before a user searches for it. A small bridge usually does not. Its cultural value must be made encounterable.

The Findability–Intelligibility–Attachment model developed in this study offers a way to diagnose this process. Physical survival is the starting point, not the endpoint. Digital findability allows users to locate the object. Narrative intelligibility allows them to understand why it matters. Participatory attachment allows them to learn, share, visit, document, or protect it. Only through these mediations can vernacular heritage become a possible resource for shared memory and community consciousness.

The study has limits. The platform audit captures a time-stamped visibility condition rather than a permanent state. Platform results may change with time, location, login status, and recommendation history. The survey provides contextual evidence, not causal proof. Local narratives around Dian Tiandeng Bridge also require further archival and oral-historical work. Future research could compare multiple vernacular heritage sites, track platform visibility over time, examine personalised search conditions, or study how local communities and platforms might collaborate on heritage findability.

Even with these limits, the Gulao case makes one point clear. In the platform age, heritage can be erased without being deleted. A bridge may stand, be photographed, and appear online, yet still fail to enter public memory as heritage. Protection therefore cannot end with stone repair, official designation, or digital upload. It must also include the name, the frame, the search pathway, and the narrative route through which people arrive at meaning. A bridge may stand, be photographed, and appear online, yet still fail to enter public memory as heritage. Protection therefore cannot end with stone repair, official designation, or digital upload. It must also include the name, the frame, the search pathway, and the narrative route through which people arrive at meaning. A bridge that survives only as a digital record is a ghost of material heritage; a bridge that stands but cannot be found is a ghost of public memory. A bridge is not protected only when it remains standing. It is protected when it can still be found as heritage.

Author Contributions:

Conceptualization, research design, and writing—original draft, Guangming Gao; methodology, theoretical framing, and manuscript revision, Guangming Gao; questionnaire distribution, field visits, data collection, and preliminary material organization, Yushan Li, Xiaoxin He, and Yunfei Lin; writing—review and editing, Guangming Gao and Musen Wang; supervision and academic guidance, Guangming Gao and Musen Wang. Guangming Gao served as the first author and corresponding author. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement:

This study involved no biomedical intervention, clinical procedure, or collection of sensitive personal information. The platform visibility audit was based on publicly accessible online information and focused on search results, platform framing, content visibility, and heritage representation rather than individual users. The supplementary questionnaire survey was conducted on a voluntary basis. Respondents were informed of the academic purpose of the study before participation, and no personally identifiable information was collected. All questionnaire data were analysed and reported in aggregate form.

Field observations, photographs, student project records, and contextual notes were used only for academic interpretation of the case. The authors took care not to disclose private information about individuals, local residents, students, or online users. The study was conducted by a research team affiliated with Wuyi University and posed minimal risk to participants and communities.

Informed Consent Statement:

The supplementary questionnaire survey was conducted on a voluntary basis. All respondents were informed of the academic purpose of the study before participation, and their submission of the completed questionnaire was regarded as informed consent to participate. No personally identifiable information was collected. All responses were anonymised, analysed in aggregate form, and used only for the purposes of this study.

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No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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Research on the Application of Internet of Things Technology in Water Operation and Management of Mountainous Counties——A Case Study of Wencheng Water Affairs

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Abstract

Water supply in mountainous counties of southern Zhejiang is featured by scattered water sources, complex pipe network terrain, difficult operation and maintenance, and weak leakage control. The traditional manual operation and maintenance mode suffers from low efficiency, high cost and delayed safety management, which cannot meet the requirements of modern water operation management. Based on the operational practice of Wenzhou Public Utilities Development Group Wencheng Water Co., Ltd., this paper constructs a four-level smart water framework of "perception layer-transmission layer-platform layer-application layer" by adopting the Internet of Things (IoT) engineering technology system. Low-power IoT, edge computing and big data analysis technologies are deeply integrated into core businesses including water quality monitoring, pipe network leakage control, pump station energy consumption management and intelligent meter reading. In view of the shortcomings of mountainous water affairs such as weak communication conditions, difficult equipment operation and maintenance, and data islands, this paper proposes a lightweight and low-cost implementation optimization scheme. The practical results show that the application of IoT technology effectively reduces pipe network leakage rate and operational maintenance costs, realizes active early warning of water supply safety and digital upgrading of operation management, and significantly improves the refined operation level of water affairs in mountainous counties, which can provide a reference for the digital transformation of water affairs in similar mountainous areas.

Keywords: Internet of Things; Smart Water Affairs; Mountainous Water Supply; Leakage Control; Water Operation Management

1. Introduction

Wencheng County is located in the mountainous region of southern Zhejiang Province, where hills and mountains dominate the natural terrain. In this geographical context, water sources, village-level reservoirs, booster pump stations, and terminal water supply facilities are widely dispersed, while transmission and distribution pipelines are often laid along mountainous terrain, resulting in long pipeline routes, complex operating conditions, and high management difficulty. Wencheng Water Affairs is responsible for the operation and management of centralized urban and rural water supply across the county. Its operation department undertakes key tasks such as pipeline network operation and maintenance, water quality supervision, non-revenue water control, energy consumption management, and metering management. Compared with urban centralized water supply systems, mountainous county-level water supply systems face more prominent constraints, including scattered facilities, difficult site access, unstable communication environments, and insufficient power supply conditions. These characteristics make the traditional operation mode increasingly unable to meet the requirements of safe, efficient, and refined water supply management.

For a long time, water supply operation in mountainous areas has relied heavily on manual inspection, on-site sampling, and household meter reading. However, due to inconvenient transportation, scattered monitoring points, and limited inspection frequency in remote mountainous villages, problems such as water quality risks, hidden pipeline leakage, abnormal pressure fluctuation, equipment failure, and inaccurate metering are often discovered with delay. This not only causes water resource waste and increases labor and maintenance costs, but also weakens the emergency response capacity and service quality of water enterprises. With the development of the Internet of Things, NB-IoT, LoRa low-power communication, smart metering, real-time monitoring, and big data analysis technologies, smart water affairs has gradually become an important direction for the digital transformation of the water industry. Existing studies have shown that IoT-based systems can support real-time water quality monitoring, pressure and flow monitoring, leakage identification, smart metering, and intelligent water distribution management, thereby improving the operational efficiency and sustainability of water supply systems (Das & Jain, 2017; García-Martín et al., 2023; Kumar, 2025; Maroli & Narwane, 2020). In China, the publication of the Specification for Communication Protocol of Internet of Things for Smart Water Affairs also provides a technical basis for the standardized development of smart water IoT systems (GB/T 38637-2020, 2020).

Although smart water affairs has attracted increasing attention at home and abroad, existing research and applications are still mainly concentrated in urban centralized water supply and drainage systems. International studies have explored IoT-based smart water distribution networks, low-power wireless communication, real-time water quality monitoring, and Industry 4.0 technologies in urban water systems, providing useful technical references for intelligent monitoring and system optimization (García-Martín et al., 2023; Marchezan, 2026; Verma et al., 2025). Domestic research has also discussed NB-IoT-based pipeline monitoring, smart water construction in small and medium-sized cities, and the application challenges of smart water technologies in municipal water supply and drainage systems (Fu, 2023; Li, 2025; Yang, 2025).

However, mountainous county-level water supply systems differ significantly from urban systems in terms of spatial distribution, communication coverage, energy supply, maintenance capacity, and investment scale. Existing high-cost, full-coverage, and heavy-platform solutions are often difficult to apply directly to small-scale and scattered water supply scenarios in mountainous counties. Research on lightweight IoT deployment, low-cost sensing, low-power communication, and practical operation optimization for decentralized rural and mountainous water supply remains insufficient (Zhang, 2026).

Based on the operational practice of Wencheng Water Affairs, this study focuses on the application and optimization of IoT technology in mountainous county water supply scenarios. Theoretically, it responds to the research gap in existing smart water studies, which tend to emphasize urban centralized pipe networks while paying insufficient attention to decentralized and lightweight IoT applications in mountainous areas. It enriches the case-based research on county-level smart water affairs and expands the understanding of IoT engineering applications under complex terrain and dispersed facility conditions. Practically, the construction of an IoT-based smart water system can help improve leakage control, strengthen water quality supervision, reduce operation and maintenance costs, optimize energy and metering management, and enhance the safety guarantee capacity of water supply services. By examining the practical experience of Wencheng, this paper aims to provide a replicable and adaptable path for the digital upgrading of water enterprises in mountainous counties, especially in regions with similar geographical and operational conditions in southwestern Zhejiang.

2. Core Pain Points of Traditional Water Operation in Mountainous Areas

2.1. Inadequate Full-Coverage Monitoring and Passive Water Safety Management

The small water sources, village-level reservoirs and booster pump stations in Wencheng County are widely scattered in remote mountainous areas. In the traditional mode, key parameters such as water quality, water level and pipe network pressure are collected manually on a regular basis with low monitoring frequency and long intervals. The operation status of the water supply system cannot be grasped in real time, and hidden dangers such as water source pollution, pipe network leakage and reservoir overflow cannot be detected timely, resulting in prominent potential risks to water supply safety.

2.2. Severe Pipe Network Leakage and Difficult Production-Sales Difference Control

Affected by geological settlement, pipe aging and terrain fluctuation, hidden leakage of mountainous pipe networks occurs frequently. In addition, the pipe network covers a wide range with extremely low efficiency of manual patrol inspection. Tiny hidden leakage cannot be eliminated for a long time, leading to a high production-sales difference rate, massive invalid water resource loss and reduced corporate profit margins, which has become the core difficulty of water operation management.

2.3. High Manual Operation Cost and Lack of Data Support for Decision-Making

Traditional operation modes rely on a large number of manual work including inspection, meter reading, water quality sampling and pump station duty, with high labor investment and low efficiency. Remote pump stations have no 24-hour on-duty personnel, and water supply load adjustment and equipment scheduling rely entirely on managers' experience without real-time data support. The dynamic optimization of pump energy consumption and dosage cannot be realized, resulting in high production and operation costs.

2.4. Isolated Business Systems and Serious Data Islands

Before the transformation, independent systems including factory automatic control, pipe network account and business charging adopted inconsistent communication protocols with no data interconnection and sharing. The Operation Department needed to manually summarize data across multiple systems for production-sales difference accounting, cost analysis and report statistics, which was time-consuming and error-prone, making integrated digital operation management impossible.

3. Design of IoT System Architecture for Mountainous Water Affairs

Combined with the characteristics of mountainous water supply in Wencheng, the company builds a smart water IoT system adapted to low-power, long-distance and weak-signal scenarios, adopting the industry-standard four-level architecture of perception layer, transmission layer, platform layer and application layer, which balances construction cost and operation practicability.

3.1. Perception Layer: Deployment of Full-Coverage Data Collection Terminals

As the core data source of the system, the perception layer deploys differentiated IoT terminals for various water supply scenarios. Water quality, liquid level and flow sensors with solar power supply are arranged at water sources to adapt to mountainous sites without municipal power supply. Energy consumption and equipment operation monitoring terminals are installed in water plants and booster pump stations to realize remote regulation of water pumps and electric valves. Pressure, flow and acoustic leakage monitoring devices are deployed at key pipe network nodes to realize DMA partition metering. Integrated monitoring equipment is installed in village-level reservoirs to monitor water level and water quality in real time. NB-IoT smart water meters are gradually popularized across the region to realize automatic collection of user water consumption data. All terminals adopt national standard communication protocols to ensure equipment compatibility.

3.2. Transmission Layer: Multi-Mode Hybrid Networking Transmission

To solve signal blind spots caused by mountain and forest occlusion, a hybrid networking mode of LoRa and NB-IoT is adopted. LoRa base stations provide low-power and long-distance signal coverage for remote mountainous sites with weak network conditions and no municipal power supply. NB-IoT narrowband IoT is applied in urban and township core areas to ensure stable data transmission. Optical fiber transmission is adopted for core stations, and edge gateways realize local data cleaning, caching and compressed transmission, avoiding data loss caused by mountainous network fluctuations and building a stable cloud-edge collaborative transmission system.

3.3. Platform Layer: Big Data Smart Water Platform

As the core hub of the system, the platform layer undertakes data access, governance, storage and intelligent analysis. It converges multi-source data such as water quality, pipe network, energy consumption and water metering through unified data interfaces, automatically cleans and calibrates abnormal data, and realizes standardized data management. The platform is equipped with AI algorithms for leakage identification, water quality early warning and energy consumption optimization, which can automatically judge equipment operation status and water supply risks. It also integrates equipment management functions to monitor terminal online status and faults in real time, providing data support for operational management.

3.4. Application Layer: Professional Business Modules for Water Operation

Based on the core work of the Operation Department, multi-dimensional business application modules are built, including water quality traceability, pipe network leakage control, pump station energy consumption scheduling, smart meter reading and revenue management, equipment operation and maintenance management, and operational data analysis. It realizes full-process visual and intelligent management of water supply, meeting the daily needs of operation and maintenance, cost control, data analysis and emergency disposal.

4. Core Application of IoT Technology in Water Operation

4.1. Full-Process Intelligent Water Quality Monitoring to Ensure Water Supply Safety

IoT sensors build a 24-hour online monitoring system covering the whole chain of “water source-water plant-reservoir-user terminal”, collecting core water quality indicators such as turbidity, pH value and residual chlorine in real time. The system will trigger pop-up window and SMS dual early warnings when data is abnormal, enabling managers to quickly locate hidden danger points and remotely adjust equipment operating parameters. The traditional 24-hour manual disposal time is shortened to 15 minutes. Meanwhile, the system can automatically optimize the dosing process of water plants according to fluctuations in raw water quality to stabilize finished water quality. All data is automatically archived, greatly reducing manual ledger work and ensuring 100% qualified water quality in the whole region.

4.2. Precise Pipe Network Leakage Control Based on Partition Metering and Intelligent Sensing

Based on the IoT DMA partition metering system, flow monitoring terminals are deployed at the inlet and outlet of township pipe networks to compare regional inflow and outflow data in real time. Combined with pipeline acoustic sensing equipment, underground hidden leakage points can be accurately located. The AI algorithm automatically calculates the regional leakage rate and generates maintenance work orders for closed-loop management, completely changing the traditional blind manual inspection mode. After the transformation, the comprehensive pipe network leakage rate of the company has been significantly reduced, effectively reducing invalid water resource loss, cutting water production and operation costs, and achieving the assessment goals of production-sales difference control.

As shown in Table 1, the application of IoT partition metering and acoustic leakage detection technology has achieved quantitative and remarkable improvement in water supply management efficiency, leakage control and emergency response capability, forming a replicable intelligent leakage governance model for mountainous water supply.

Table 1. Improvement Effects of IoT-Based Intelligent Leakage Control in Mountainous Water Supply Pipe Networks

Indicator	Before IoT Transformation	After IoT Transformation	Optimization Effect
Comprehensive Pipe Network Leakage Rate	16.8%	12.6%	Reduced by 4.2%
Manual Pipe Inspection Workload	Full manual patrol coverage	Partial intelligent inspection	Reduced by 65%
Water Quality Abnormal Response Time	24 hours	15 minutes	99% time reduction
Annual Invalid Water Loss	High continuous loss	180,000 tons saved annually	Great water resource conservation

4.3. Intelligent Pump Station Scheduling to Reduce Production Energy Consumption

After the intelligent IoT transformation of mountain booster pump stations, the system can automatically adjust the pump frequency and operating conditions according to real-time pipe network pressure and water load data, realizing peak-load shifting and energy-saving operation. The equipment load is reduced during low water consumption periods and pressure is stabilized in advance during peak periods, replacing the traditional manual duty and experience-based scheduling mode. It not only stabilizes pipe network water supply pressure, but also greatly reduces pump station power consumption, and cancels night duty in remote stations, saving a lot of labor and energy costs.

4.4 Full Coverage of Smart Water Meters for Efficient Revenue Management

The fully popularized NB-IoT smart water meters support automatic remote meter reading and data uploading, realizing automatic water fee accounting and completely eliminating manual household meter reading work. The built-in water consumption anomaly identification model can accurately identify water theft, private pipeline connection and abnormal water use, reducing water fee loss. Meanwhile, remote valve closing and arrears management functions effectively improve water fee recovery efficiency and the refinement level of revenue management.

4.5. Digital Data Analysis to Support Scientific Operational Decision-Making

The IoT data platform breaks cross-system data barriers, automatically summarizes core operational indicators such as production-sales difference, energy consumption, water quality and operation cost, and generates visual dashboard and monthly operational reports. Relying on real-time and historical data, the Operation Department can accurately locate areas with high energy consumption and high leakage, formulate targeted schemes for pipe network transformation, equipment renewal and cost control, and promote the transformation of water operation from empirical decision-making to data-driven scientific decision-making.

5. Construction Difficulties and Optimization Countermeasures

5.1. Core Construction Difficulties

Firstly, the mountainous area has complex communication conditions with weak signals in remote sites due to mountain and forest occlusion, and the power supply stability of equipment without municipal power is insufficient. Secondly, scattered mountainous monitoring points lead to high one-time investment in full-scale IoT transformation with a long capital return cycle. Thirdly, equipment from multiple manufacturers has inconsistent protocols, resulting in difficult data docking; in addition, professional IoT operation and maintenance personnel are scarce in mountainous areas, leading to low efficiency of equipment fault disposal. Fourthly, the humid and variable mountainous environment easily causes sensor data drift, resulting in data distortion and judgment deviation.

5.2. Optimization Countermeasures

In view of the above difficulties, the company adopts a lightweight phased transformation scheme, prioritizing the upgrading of core pipe networks and key water source points, and gradually promoting full-scale transformation. Special financial subsidies are applied to alleviate capital pressure. LoRa base station signal compensation and photovoltaic energy storage power supply are adopted to solve mountainous signal and power supply problems. Unified equipment access protocols and technical standards are formulated to avoid data docking barriers. An internal part-time operation and maintenance team is established, with regular professional training jointly conducted by manufacturers to build a grid-based operation and maintenance mechanism. Meanwhile, a data security protection system is built through data encryption, authority grading and regular equipment calibration to ensure the authenticity, safety and effectiveness of IoT data.

6. Application Effects, Prospects and Conclusion

The implementation of the IoT-based smart water system has brought comprehensive and remarkable improvements to the operational management of Wencheng mountainous water supply. In terms of water supply safety, the full-time real-time water quality monitoring mechanism realizes rapid early warning and emergency disposal of potential risks, achieving a

100% water quality compliance rate and effectively guaranteeing rural and urban drinking water safety. In terms of economic benefits, the system significantly reduces pipe network leakage rates, realizing effective conservation of water resources, while the intelligent scheduling of pump stations greatly cuts energy consumption and manual operation costs, substantially improving the overall operational efficiency and economic benefits of water enterprises. In terms of daily management, intelligent monitoring and automatic data statistics eliminate massive manual inspection, ledger sorting and data reconciliation work, successfully transforming the traditional extensive manual management mode into refined, digital and intelligent water operation management.

In view of the long-term development of mountainous water affairs, IoT technology will continue to serve as the core support for digital upgrading. Future optimization directions include the construction of a digital twin water supply platform to realize visual simulation and intelligent scheduling of pipe network operation, training AI prediction models based on long-term accumulated IoT monitoring data to achieve predictive maintenance of aging pipe networks and early warning of water quality and water load changes, and expanding IoT application scenarios to recycled water utilization, flood prevention and drought resistance management. Through continuous technological iteration, a fully covered and integrated smart water service system will be built to promote the high-quality development of mountainous water supply.

In conclusion, restricted by complex terrain and scattered water supply characteristics, traditional manual management modes can no longer adapt to the modernization needs of mountainous county water affairs. This paper constructs a four-layer IoT smart water system architecture suitable for mountainous working conditions, and applies low-power communication, edge computing and big data analysis technologies to solve typical industry problems including monitoring blind areas, serious pipe network leakage, high energy consumption and data fragmentation. Adopting a lightweight and phased construction strategy, the research realizes coordinated improvement of water supply safety, economic benefits and management efficiency. It is verified that mountainous water smart transformation should adopt localized and low-cost IoT solutions rather than copying urban mature models, so as to continuously empower the refined and intelligent upgrading of county water operation and management.

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Research on the Application of Internet of Things Technology in Intelligent Operation and Maintenance of Water Supply Plants in Mountainous Towns

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Abstract

Mountainous township water supply plants in southern Zhejiang generally suffer from scattered layout, difficult operation and maintenance, delayed water quality management, high pipe network leakage rate and insufficient digitalization level. Based on the practical operation and maintenance experience of Yuhu Water Supply Plant, this paper explores the whole-process application effect of Internet of Things (IoT) technology in township water supply. By adopting water quality sensing terminals, wireless transmission technology, PLC intelligent control and smart water cloud platform, an intelligent operation and maintenance system adapted to complex mountainous working conditions is constructed. The system realizes real-time monitoring, intelligent regulation and early warning disposal of water intake, water production, water storage and pipe network water supply. The results show that the IoT system significantly improves water quality safety guarantee capability, equipment operation efficiency, pipe network leakage control and energy-saving performance, and effectively solves various drawbacks of traditional manual operation modes. The research can provide practical references for the digital and intelligent upgrading of similar mountainous township water plants.cal foundation for optimizing industrial space policies and planning supply strategies.

Keywords: Internet of Things; Smart Water Affairs; Township Water Supply Plant; Intelligent Operation And Maintenance; Water Quality Management; Pipe Network Leakage Control

1. Introduction

With the continuous advancement of digital rural construction and urban−rural water supply integration, township water supply plants have become important infrastructure carriers for ensuring rural drinking water safety and improving grassroots public service capacity. Compared with large urban water plants, township water supply plants usually face more complex operating environments, weaker technical support capacity, and more limited operation and maintenance resources. Therefore, promoting intelligent monitoring, automatic control, and refined management in township water supply plants is of great significance for improving water supply safety, reducing operation costs, and enhancing service quality. Existing studies have shown that IoT-based monitoring, intelligent scheduling, NB-IoT communication, PLC automatic control, and data platform integration can effectively support real-time perception, remote regulation, abnormal early warning, and operational decision-making in water supply systems (Pang, 2025; Tian & Wang, 2022; Yang & Wang, 2025; Zhang, 2023). In this context, the intelligent renovation of township water supply plants is not only a technical upgrading process, but also an important practical path for transforming grassroots water supply management from experience-based operation to data-driven governance.

Wencheng County is located in the mountainous area of southern Zhejiang Province, where township water plants are generally characterized by unstable raw water sources, long mountain-laid pipe networks, scattered and remote stations, difficult transportation access, and insufficient operation manpower. These geographical and managerial characteristics make water supply operation more vulnerable to sudden changes in water quality, equipment failure, pressure fluctuation, pipeline leakage, and energy consumption uncertainty. Yuhu Water Supply Plant of Wencheng Water Affairs Co., Ltd. is a typical mountainous township water supply plant. The plant serves 22 administrative villages in Yuhu Town, covering a permanent population of approximately 21,000 people, with a daily water production capacity of 3,500 cubic meters. It is equipped with complete water production facilities, a 47-kilometer mountainous water supply pipe network, and 12 remote booster pumping stations. Before the intelligent renovation, the plant mainly relied on manual inspection, manual regulation, and paper-based records, which made it difficult to achieve timely water quality warning, accurate equipment fault diagnosis, precise leakage control, and scientific energy consumption management. Similar studies have also pointed out that township and village water supply systems urgently need lightweight, low-cost, and practical IoT solutions adapted to dispersed facilities and complex grassroots management conditions (Lei & Cheng, 2024; Li, 2024; Liu, 2026; Yu & Li, 2026).

To address these operational bottlenecks, Yuhu Water Supply Plant launched an IoT-based smart water supply renovation project in 2023. The project introduced IoT perception, intelligent control, and big data analysis into the whole process of raw water intake, water production, disinfection, water quality monitoring, pump station operation, pipe network transmission, leakage control, and user-side metering. Through the deployment of online water quality sensors, flow and pressure monitoring terminals, NB-IoT communication devices, PLC automatic control systems, acoustic leakage detection equipment, and a unified data management platform, the plant gradually realized 24-hour online monitoring, remote control of key equipment, abnormal alarm push, and closed-loop maintenance management. International studies have also demonstrated that low-power wireless networks, autonomous IoT monitoring devices, acoustic sensing systems, and AI-assisted water management platforms can improve the reliability, sustainability, and response efficiency of water distribution systems (García-Martín et al., 2023; Okoli & Kabaso, 2024; Poudel & Mohammadi, 2026; Silva et al., 2025; Slaný et al., 2025). These findings provide technical support and comparative references for the intelligent transformation of small mountainous township water plants.

However, current research on smart water affairs at home and abroad still focuses mainly on large-scale urban water plants, urban distribution networks, and comprehensive smart water platforms. Relatively few studies have examined practical IoT renovation paths for small township water plants in mountainous areas, especially under constraints such as limited investment, dispersed facilities, weak communication coverage, and insufficient professional operation manpower. Based on the author′s long-term front-line management experience as the person in charge of Yuhu Water Supply Plant, this paper systematically summarizes the application process, implementation effects, existing problems, and optimization strategies of IoT technology in a grassroots mountainous water supply project. The study aims to provide a practical and replicable reference for the intelligent renovation of township water supply plants, enrich the application cases of IoT technology in rural drinking water management, and support the digital transformation of county-level water enterprises under complex mountainous conditions.

2. Main Problems of Traditional Operation and Maintenance of Mountainous Township Water Plants

The traditional manual operation mode shows poor adaptability to mountainous water supply conditions and restricts the improvement of water service quality. In terms of water quality management, the raw water of mountainous water plants is mainly mountain surface water, which is vulnerable to rainfall, soil erosion and non-point source pollution, leading to frequent water quality fluctuations. Traditional manual sampling conducted only several times a day cannot realize 24-hour continuous monitoring, making it impossible to detect sudden water quality abnormalities in a timely manner. In addition, disinfection and coagulant dosing are completely adjusted by manual experience, resulting in inaccurate dosing volume, excessive or insufficient residual chlorine, and potential drinking water safety risks.

In terms of equipment operation and maintenance, the pumping stations and water supply equipment are widely distributed in remote mountainous areas. Traditional manual inspection is time-consuming and inefficient. The operating status and energy consumption data of water pumps, dosing devices and motors cannot be monitored in real time. Equipment overload, shutdown and agent shortage are often discovered belatedly, which easily causes water supply interruption. Moreover, equipment maintenance mainly relies on post-fault repair without predictive management, resulting in short service life and high energy consumption.

In terms of pipe network management, mountainous water supply pipe networks feature complex terrain, long pipelines and aging sections, with highly concealed hidden leakage and micro-leakage. Traditional manual meter reading and sectional investigation fail to monitor real-time pipe network pressure and flow, leading to delayed leakage detection and long repair cycles. The plant maintains a high water production and sales difference rate, causing serious waste of water resources and operation costs. Meanwhile, traditional operation leads to fragmented data. Production, water quality, energy consumption and pipe network data are recorded on paper without integrated analysis and intelligent scheduling. Water supply regulation purely depends on manual experience, resulting in unstable water pressure and unreasonable resource allocation during peak water consumption periods.

3. Overall Architecture of IoT Intelligent Operation and Maintenance System for Mountainous Water Plants

In view of the inherent limitations of mountainous water plants, including weak network coverage, limited budget and complex terrain conditions, Yuhu Water Supply Plant has constructed a four-layer IoT intelligent operation and maintenance system, consisting of perception and collection layer, network transmission layer, edge control layer and cloud application layer. Abandoning complicated and high-cost traditional architectures, the system features low investment, strong environmental adaptability and convenient maintenance, which is highly suitable for the intelligent upgrading of grassroots mountainous water supply facilities.

3.1. Perception and Collection Layer

As the basic data acquisition unit of the intelligent system, the perception layer covers the whole key procedures of water production and pipe network water supply. Multi-parameter water quality sensors are deployed at water intakes, sedimentation tanks, clean water tanks and water delivery mains to collect real-time water quality indicators including turbidity, pH value, residual chlorine and dissolved oxygen. Operation monitoring modules are installed on water pumps and dosing equipment to dynamically acquire the operating current, voltage, frequency and real-time status of electromechanical equipment.

The entire water supply pipe network is divided into independent metering zones equipped with NB-IoT flow and pressure monitoring terminals. Liquid level sensors and safety monitoring devices are also deployed to realize comprehensive data collection of water quality changes, electromechanical equipment operation and pipe network operating conditions, covering all key monitoring nodes of the water supply system.

3.2. Network Transmission Layer

A hybrid communication architecture is adopted to adapt to complex mountainous environments. Industrial Ethernet is deployed in centralized plant areas to ensure low-latency data transmission and real-time equipment linkage control. For remote mountain pumping stations and pipe network monitoring points without wired network coverage, low-power NB-IoT wireless transmission technology combined with solar energy storage power supply systems is applied, effectively solving the difficulties of difficult wiring, insufficient power supply and unstable signal transmission in mountainous regions.

Furthermore, the system adopts encrypted data transmission and exclusive equipment authentication mechanisms to avoid data tampering and loss, ensuring the confidentiality, stability and integrity of water supply data during transmission.

3.3. Edge Control Layer

The edge control layer realizes local intelligent linkage control based on PLC controllers, avoiding operational risks caused by network delay of cloud remote control. According to real-time monitoring data of raw water quality, pipe network pressure and water tank liquid level, the system can automatically adjust dosing volume, water pump operating frequency and the number of operating units, achieving precise dosing, constant-pressure water supply and energy-efficient operation.

In addition, the system is embedded with a local fault self-protection function. When abnormal conditions such as equipment overload, excessive water quality indicators and drastic liquid level fluctuations occur, the system automatically triggers emergency responses including equipment shutdown and acousto-optic alarm to eliminate water supply safety hazards in the first place.

3.4. Cloud Application Layer

The cloud application layer is built on a lightweight smart water management platform compatible with both web and mobile terminals. It integrates core functions including real-time monitoring, intelligent early warning, data statistical analysis, full-life-cycle equipment management and automatic report generation. The platform visually displays the entire water production process and pipe network operating status, automatically pushes alarm notifications and generates operation and maintenance work orders once system abnormalities are detected.

The platform automatically summarizes and stores long-term operational data throughout the year, completely replacing the traditional manual paper-based recording mode and realizing comprehensive digitalization, visualization and intelligence upgrading of water supply operation and maintenance management.

4. Implementation Measures of IoT System

To minimize the impact of intelligent renovation on residents' daily water supply, the plant adopts a phased and peak-staggered construction scheme for IoT system upgrading. All construction work including equipment installation, circuit layout, terminal debugging and platform joint commissioning is arranged avoiding morning and evening water consumption peaks, with segmented and short-time night construction adopted. No large-scale or long-term water supply interruption occurred during the whole renovation period, which effectively guaranteed stable domestic water supply for local residents.

4.1. Optimized Equipment Selection Adapted to Mountainous Environments

Considering the harsh climatic and geographical characteristics of mountainous areas such as low temperature, high humidity and off-grid power supply in partial remote areas, all monitoring and control devices adopt industrial-grade equipment with waterproof, dustproof and low-temperature resistance performance. Solar energy storage power supply systems are configured for off-grid monitoring points, and self-cleaning components are installed for all water quality sensors. The optimized equipment selection effectively reduces equipment failure rate and daily maintenance workload, and greatly improves the long-term operational stability of the system in complex mountainous environments.

4.2. Personnel Training and System Operation Guarantee

In view of the uneven digital operation capabilities of front-line staff, systematic and targeted practical training on intelligent system operation is carried out, covering daily equipment inspection, platform operation, fault diagnosis and disposal, as well as data query and statistical analysis. Simplified visual operation manuals are compiled, and one-on-one targeted guidance is provided for employees with weak digital operation skills. Standardized training ensures that all operation and maintenance personnel can independently complete daily system operation and fault handling, providing solid technical and talent support for the long-term stable and efficient operation of the intelligent system.

5. Analysis of System Application Effects

Since the full operation of the IoT intelligent operation and maintenance system for more than one year, the traditional manual operation mode has been completely transformed, achieving remarkable improvements in water supply safety, operation efficiency, energy conservation and leakage control. In terms of water quality guarantee, the system realizes 24-hour uninterrupted full-process water quality monitoring and intelligent dosing regulation, solving the problems of inaccurate manual dosing and delayed water quality monitoring. The annual qualified rate of finished water quality reaches 100%. All potential water quality abnormalities are disposed of timely, with zero water quality complaints and safety accidents throughout the year (Table 1).

In terms of operation and maintenance management, remote real-time monitoring replaces frequent full-scale manual inspections, greatly reducing human input. The manual inspection cost is reduced by 65%, and the fault detection time is shortened from 24 hours to within 10 minutes. Equipment shutdown and night water supply interruption are completely eliminated. Equipment maintenance is transformed from post-fault repair to predictive maintenance, significantly improving equipment stability and service life.

In terms of energy conservation and leakage control, intelligent variable-frequency regulation of water pumps and precise agent dosing effectively reduce water production energy consumption and chemical consumption. The unit water production power consumption is reduced by 11.5%, and agent consumption is decreased by 8%, saving more than 100,000 RMB in electricity and chemical costs annually. Supported by segmented pipe network monitoring data, multiple hidden mountain leakage points are accurately detected and repaired. The comprehensive pipe network leakage rate is reduced from 13.2% to 7.8%, effectively reducing water resource waste and improving water utilization efficiency.

In terms of digital management, the system automatically generates water quality, energy consumption and operation and maintenance reports, completely replacing manual paper recording. It significantly improves work efficiency, standardizes water supply management processes, and meets the requirements of industry supervision and enterprise standardized management.

Table 1. Core operational indicator comparison before and after IoT system renovation

Evaluation Indicators	Before Renovation (2022)	After Renovation (2024)	Improvement Effect
Finished water quality compliance rate	97.6%	100%	Completely eliminate water quality non-compliance risks
Pipe network water leakage rate	13.2%	7.8%	Significantly reduce water resource waste
Unit water production power consumption	Baseline value	Reduced by 11.5%	Realize efficient energy-saving operation
Agent consumption for water production	Baseline value	Reduced by 8.0%	Avoid excessive chemical dosing
Manual inspection labor cost	High-frequency full-area manual inspection	Reduced by 65%	Greatly optimize human resource allocation
Average equipment fault discovery time	24 hours	≤10 minutes	Realize ultra-fast fault early warning
Manual paper recording workload	Full manual recording	100% automatic electronic report	Realize standardized digital management

6. Existing Problems and Optimization Directions

Restricted by mountainous geographical conditions, some extremely remote pipe network monitoring points suffer from weak signals and delayed data upload. In addition, the current system only relies on basic flow and pressure data for leakage analysis, resulting in limited identification accuracy of micro-leakage. Meanwhile, data interconnection with the group's general platform has not yet been realized. Targeted optimization and upgrading will be carried out in the future. Signal amplification equipment and long-distance communication terminals will be deployed to solve mountain signal instability. Acoustic leakage detection sensors will be added to optimize the leakage analysis algorithm and further reduce the pipe network water sales difference. The data interface between superior and subordinate platforms will be opened to realize unified data aggregation and global intelligent scheduling, so as to continuously improve the intelligent operation level of the water plant.

7. Conclusion

Taking the intelligent renovation of Yuhu Water Supply Plant as a practical case, this paper explores the application value of IoT technology in mountainous township water supply operation and maintenance. The practice verifies that the IoT operation and maintenance system adapted to mountainous working conditions can effectively solve the core pain points of traditional water plants, including insufficient water quality control capacity, low operation efficiency, high leakage rate, energy waste and non-standard management, realizing comprehensive improvements in water supply safety, operation efficiency, energy conservation and digital management with remarkable input-output benefits.

As a grassroots water management staff, I have fully participated in the scheme design, construction implementation and daily operation of the IoT system, and deeply recognized the enabling effect of IoT technology on the traditional water supply industry. Under the trend of digital water affairs development, township water supply plants should continuously promote intelligent upgrading relying on IoT and big data technologies, improve rural water supply guarantee capacity and refined management level, and provide solid technical support for urban-rural water supply integration and long-term stable rural drinking water safety.

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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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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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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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Analysis of the Causes of Excessive Manganese and Discussion on Treatment Measures in a Waterworks in Cangnan County

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Abstract

Excessive manganese in the effluent of a waterworks in Cangnan County not only leads to sensory abnormalities of drinking water but also poses a potential threat to human health, which has become an urgent water quality problem to be solved. In this study, flame atomic absorption spectrophotometry was adopted to determine the manganese concentration in water samples at each treatment stage, so as to evaluate the actual effect of different manganese removal processes. Aiming at the problem of excessive manganese in raw water, the waterworks optimized the conventional water treatment process by taking measures such as strengthening pre-chlorination and adding potassium permanganate composite salt. The results showed that both measures could effectively oxidize soluble divalent manganese into insoluble tetravalent manganese, which was then intercepted and removed by the filter, and the manganese content in the final effluent was stably controlled below the limit value of 0.1mg/L specified in GB 5749-2022. This study not only effectively solved the problem of excessive manganese in the waterworks but also provided a practical and feasible technical reference for the treatment of excessive manganese in reservoir water sources of similar waterworks in southern China.

Keywords: Excessive Manganese in Water; Reservoir Water Source; Pre-Chlorination; Potassium Permanganate Composite Salt; Manganese Removal Technology

1. Introduction

The "Sanitary Standards for Drinking Water" (GB 5749-2022) implemented in China clearly stipulates that the limit value of manganese in drinking water is 0.1mg/L (State Administration for Market Regulation of the People's Republic of China, 2022). Manganese is a trace element necessary for the human body, but long-term intake of water with excessive manganese content will cause serious harm to the human body, and also lead to sensory quality problems of water body. In terms of human health hazards, excessive manganese mainly damages the nervous system, blood system, respiratory system and digestive system of the human body, and even causes manganese poisoning in severe cases, showing symptoms such as muscle spasm, tremor, bradykinesia, anemia, bronchitis, and emotional instability (Cheng et al., 2021; Li, 2022). In terms of water body sensory quality, excessive manganese will cause color, odor and taste abnormalities of tap water, and even form brown precipitates in the water pipeline, which affects the normal use of water by residents. Therefore, effective control of manganese content in drinking water is an important part of waterworks to ensure water supply safety.

A waterworks in Cangnan County, Wenzhou City, with a daily water supply capacity of 20,000 tons, is an important urban water supply facility in the southern part of Cangnan County. The water treatment process adopted by the waterworks is a conventional process of folded plate-inclined tube coagulation and sedimentation + valveless filter filtration + sodium hypochlorite disinfection. The raw water is taken from Tiechang Reservoir and Yunzhe Reservoir in the jurisdiction. Since the summer of 2023, the water quality monitoring data of the waterworks showed that the manganese content in the effluent exceeded the standard seriously, which directly threatened the water supply safety of the residents in the water supply area. Through on-site investigation and sampling analysis, it was found that the main reason for the excessive manganese in the effluent was the serious manganese pollution of the two reservoir water sources, which was closely related to the local geological conditions and seasonal environmental changes.

Aiming at the problem of excessive manganese in the raw water of the reservoir, this study carried out a systematic analysis on the causes of excessive manganese in the water source, and tested and optimized different manganese removal processes on the basis of the original water treatment process of the waterworks. By determining the manganese concentration in water samples at each treatment stage with flame atomic absorption spectrophotometry, the optimal manganese removal process parameters were screened out, and practical and feasible treatment measures were formulated, which realized the stable up-to-standard of manganese content in the effluent of the waterworks. The research results can provide technical reference for the treatment of excessive manganese in similar reservoir water sources in coastal areas of southern China.

2. Test Materials and Methods

2.1. Main Reagents and Materials

Manganese standard sample (1000mg/L, National Institute of Metrology, China, No.: GBW(E) 080157, Batch No.: 21011); Nitric acid (guaranteed reagent, Changshu Zhitang Fine Chemical Co., Ltd.); Experimental water was ultrapure water (18.2MΩ·cm, Sichuan Youpu Purification Equipment Co., Ltd.). All glassware used in the test was soaked in nitric acid solution (1:9, V/V) for 24h, and rinsed with ultrapure water for 3 times before use to avoid manganese contamination.

2.2. Main Instruments and Equipment

AA-6880 flame atomic absorption spectrophotometer (Shimadzu Instruments (Suzhou) Co., Ltd.); Manganese hollow cathode lamp (Shimadzu Corporation); 0.45μm microporous filter membrane (Shanghai Xinya Purification Materials Co., Ltd.); Polyethylene sampling bottle

(500mL, Nanjing Xiangrui Experimental Equipment Co., Ltd.); Digital pH meter (Shanghai Leici Instrument Factory).

2.3. Instrument Working Parameters

In order to ensure the accuracy and precision of manganese content determination, the working parameters of the atomic absorption spectrophotometer were optimized, and the optimal parameters were set as follows: Lamp current 10mA; Determination wavelength 279.5nm; Monochromator slit width 0.2nm; Fuel gas was high-purity acetylene, oxidant gas was compressed air; Fuel gas gauge pressure 0.09MPa, oxidant gas gauge pressure 0.35MPa; Sample injection method was manual continuous sample injection; The measurement mode was absorbance mode.

2.4. Test Operation Steps

2.4.1. Sample Collection and Pretreatment

According to the "Technical Specification for Monitoring of Drinking Water Quality" (HJ/T 91-2002), water samples were collected at the raw water intake, coagulation and sedimentation tank effluent, filter effluent and final effluent of the waterworks (Phase I and Phase II systems). For the determination of dissolved manganese, the water sample was immediately filtered through a 0.45μm microporous filter membrane after collection, and the filtrate was collected in a clean polyethylene sampling bottle. 1.5mL of concentrated nitric acid was added to each liter of filtrate for acidification (to make the pH < 2) for fixation, and the sample was stored in a cool and dark place for testing within 24h.

2.4.2. Sample Determination

Before the test, the exhaust system, gas cylinder and atomic absorption spectrophotometer were turned on in turn, and the manganese hollow cathode lamp was installed for preheating for 30min to ensure the instrument was in a stable working state. The manganese standard solution series with mass concentrations of 0.0mg/L, 0.1mg/L, 0.2mg/L, 0.4mg/L, 0.6mg/L and 0.8mg/L were prepared by gradient dilution, and the standard working curve was drawn by determining the absorbance of the standard series under the optimal instrument parameters. Under the same test conditions, the absorbance of the water sample to be tested was determined, and the blank test was carried out simultaneously to eliminate the system error. The mass concentration of manganese in the water sample was calculated according to the standard working curve and the absorbance value of the sample to be tested.

3. Results and Analysis

3.1. Causes of Excessive Manganese in Reservoir Raw Water

The raw water of the waterworks is taken from Tiechang Reservoir and Yunzhe Reservoir. The geological stratum in the surrounding area of the two reservoirs is rich in manganese-containing minerals, and a large amount of manganese ions are deposited at the bottom of the reservoirs for a long time, mainly in the form of stable manganese-containing complexes, which are not easy to be naturally oxidized and released into the water body under normal conditions. However, affected by the high temperature climate in summer, the surface water temperature of the reservoir rises rapidly, the water density decreases, and the obvious thermal stratification phenomenon occurs in the water body, which hinders the convection and exchange of the upper and lower water bodies. The dissolved oxygen in the upper water body cannot be transferred to the bottom of the reservoir, resulting in a serious anoxic environment at the reservoir bottom. Under the anoxic condition, the insoluble tetravalent manganese in the bottom sediment is reduced to soluble divalent manganese, which is released from the sediment and floats up to the upper water body with the water flow, resulting in a sharp increase of manganese content in the raw water of the reservoir.

The water quality monitoring data showed that the manganese content in the raw water of Tiechang Reservoir increased to a maximum of 0.8mg/L in summer, and the manganese content in the raw water of Yunzhe Reservoir was about 0.6mg/L under normal conditions. Due to the low water intake height of Yunzhe Reservoir, it is easily affected by the disturbance of water discharge from the bottom outlet of the reservoir. In mid-September 2023, the manganese content in the raw water of Yunzhe Reservoir further rose to more than 1.0mg/L due to the bottom discharge disturbance, which far exceeded the limit value of drinking water and brought great pressure to the water treatment of the waterworks.

3.2. Analysis of Conventional Manganese Removal Oxidants for Waterworks

The core of chemical oxidation manganese removal technology for waterworks is to select appropriate oxidants to oxidize soluble divalent manganese in raw water into insoluble tetravalent manganese dioxide precipitate, which is then removed by coagulation, sedimentation and filtration processes. Common oxidants available for waterworks include aeration, chlorine dioxide, sodium hypochlorite, ozone and potassium permanganate. The advantages and disadvantages of various oxidants in manganese removal application are analyzed as follows (Table 1).

Table 1. Comparison of advantages and disadvantages of common oxidants for manganese removal in waterworks

Oxidant	Advantages	Disadvantages
Aeration	Low cost, simple operation	Low oxidation capacity, limited manganese removal effect for high-concentration manganese; easy to cause physical disturbance and affect flocculation and sedimentation
Chlorine dioxide	Fast oxidation speed, good manganese removal effect	On-site preparation is required; special equipment is needed; easy to cause excessive chlorite in effluent
Sodium hypochlorite	Easy to store and transport, simple dosing	Only effective under high pH (pH>9.5); long reaction time; easy to cause excessive disinfection by-products and aluminum
Ozone	Ultra-fast oxidation speed, no residual pollution	High cost, need special generation equipment; easy to oxidize manganese to heptavalent state if the dosage is too high
Potassium permanganate	Good oxidation effect, short reaction time (completed in a few minutes); high removal efficiency	The dosage must be accurately controlled; excessive dosage will cause "red water" phenomenon in effluent

3.3. Targeted Manganese Removal Measures and Effect of the Waterworks

The waterworks has two sets of independent coagulation and sedimentation tank systems (Phase I and Phase II), which are respectively responsible for the treatment of raw water from Tiechang Reservoir and Yunzhe Reservoir. According to the different manganese content in the raw water of the two reservoirs, the waterworks adopted targeted manganese removal measures: strengthening the pre-chlorination process for the raw water with low manganese content (Phase I), and adding potassium permanganate composite salt for the raw water with high manganese content (Phase II). The original coagulation, sedimentation and filtration process of the waterworks was not changed, and the manganese removal transformation was completed on the basis of the original process, which realized the advantages of low transformation cost and quick effect.

3.3.1. Manganese Removal Measures and Effect of Phase I Water System (Tiechang Reservoir Raw Water)

The water quality test showed that the total manganese content in the raw water of Tiechang Reservoir was 0.45mg/L, and the dissolved divalent manganese content after filtration was 0.32mg/L. The divalent manganese content was relatively low, so it was decided to adopt the measure of strengthening the pre-chlorination process in the Phase I coagulation tank to realize manganese removal, with sodium hypochlorite as the oxidant. The oxidation reaction formula of sodium hypochlorite and divalent manganese is as follows: $Mn_2^{+}+ClO^{-}+H_2O=MnO_2\downarrow+Cl^{-}+2H^{+}$

It can be seen from the reaction formula that the reaction produces H+ ions, which will inhibit the progress of the oxidation reaction. Therefore, the reaction can be accelerated in an alkaline environment. Based on the reaction principle and the actual water quality of the waterworks, the key process parameters of strengthened pre-chlorination were optimized as follows:

(1) Determination of pre-chlorination dosage: According to the reaction stoichiometric ratio, 1mol of divalent manganese requires 1mol of sodium hypochlorite for oxidation. Combined with the actual divalent manganese content of 0.32mg/L in the raw water, and considering the consumption of sodium hypochlorite by other reducing substances in the water, the effective chlorine dosage of pre-chlorination was set to 0.5mg/L, that is, the dosage of 10% sodium hypochlorite solution was increased to 5kg per 1000 tons of water.

(2) Adjustment of raw water pH value: Relevant literature shows that the oxidation reaction of sodium hypochlorite and divalent manganese can proceed rapidly when the pH value is above 9.5 (Li et al., 2023). However, considering that the excessive pH value of the effluent will lead to the problem of excessive aluminum, the raw water pH value was adjusted to 8.5 by adding alkali in advance, which provided a weak alkaline environment for the oxidation reaction and avoided the secondary water quality problem caused by excessive pH value.

(3) Strengthening water quality monitoring: The content of disinfection by-products and aluminum in the filter effluent and final effluent was regularly determined to ensure that all water quality indicators meet the standard while removing manganese.

After the implementation of the above measures, the water quality monitoring results showed that the manganese content in the filter effluent of the Phase I water system decreased from 0.45mg/L of raw water to below 0.05mg/L, which was far lower than the limit value of 0.1mg/L specified in GB 5749-2022, and the disinfection by-products and aluminum content in the effluent were all within the standard range. The strengthened pre-chlorination process achieved an ideal manganese removal effect, and the operation was simple and the cost was low, which was suitable for the long-term operation of the Phase I water system.

3.3.2. Manganese Removal Measures and Effect of Phase II Water System (Yunzhe Reservoir Raw Water)

The water quality test showed that the total manganese content in the raw water of Yunzhe Reservoir was as high as 1.10mg/L, and the dissolved divalent manganese content after filtration was 0.81mg/L. The divalent manganese content was much higher than that of the Phase I raw water, and the strengthened pre-chlorination process could not achieve the standard manganese removal effect. Therefore, it was decided to adopt the measure of adding potassium permanganate composite salt for manganese removal. The mass ratio of potassium permanganate in the composite salt was 50%, which had the advantages of high oxidation efficiency and easy dosing. The oxidation reaction formula of potassium permanganate and divalent manganese under neutral conditions is as follows: $2KMnO_4+3Mn_2^{+}+2H_2O=5MnO_2\downarrow+2K^{+}+4H^{+}$

According to the reaction formula, the theoretical dosage of potassium permanganate is 1.91 times the mass concentration of divalent manganese. Considering that the manganese dioxide precipitate generated in the reaction has an adsorption effect on divalent manganese, and the organic matter in the raw water will consume part of potassium permanganate, the actual dosage of potassium permanganate is generally 1.5~2.5 times the mass concentration of divalent manganese (Ma et al., 2023). In order to determine the optimal dosage of potassium permanganate composite salt, the manganese oxidation stirring test was carried out in the laboratory first, and then the industrial application was carried out according to the test results. The specific implementation measures are as follows:

(1) Laboratory stirring test to determine the optimal dosage: Potassium permanganate composite salt solution with a certain concentration was prepared, and 1L of raw water of Yunzhe Reservoir was taken in each beaker. The potassium permanganate composite salt solution was added to each beaker according to 3~5 times the mass concentration of divalent manganese (0.81mg/L), and stirred at a constant speed for 2min to make it fully react. The reaction solution was filtered with a 0.45μm microporous filter membrane, and the manganese content in the filtrate was determined. The test results showed that when the dosage of potassium permanganate composite salt was 3.6 times the mass concentration of divalent manganese (i.e., 2.9mg/L), the manganese content in the filtrate was the lowest and met the standard. Therefore, the optimal dosage of potassium permanganate composite salt was determined to be 2.9kg per 1000 tons of water.

(2) Determination of reasonable dosing point: The dosing point of potassium permanganate composite salt was selected at the front end of the folded plate reaction tank (before adding alum).

When the pH value of the raw water is above 6.5, the oxidation reaction of potassium permanganate and divalent manganese can be completed in a few minutes (Li et al., 2023). The folded plate reaction tank has a good mixing effect, which can make the potassium permanganate composite salt fully contact and react with the raw water, and the manganese dioxide precipitate generated by the reaction can be adsorbed and flocculated with the alum floc, which is convenient for subsequent sedimentation and filtration removal.

(3) Dosing method and operation control: The potassium permanganate composite salt solution with a certain concentration was prepared in the chemical dosing tank of the waterworks, and a digital metering pump was used to add the composite salt into the raw water pipe according to the raw water flow rate and the optimal dosage. The water sample was taken from the second or third row of the folded plate reaction tank for manganese content determination, and the dosing amount was adjusted in real time according to the test results. If the filtrate showed purple-red, it indicated that the dosage of potassium permanganate composite salt was excessive, and the dosage should be reduced immediately to avoid the "red water" phenomenon in the effluent. At the same time, the normal operation of the valveless filter was ensured, and the backwashing frequency of the filter was appropriately increased to prevent the manganese dioxide precipitate from blocking the filter material and affecting the filtration effect.

(4) Key points of process operation: In the process of adding potassium permanganate composite salt for manganese removal, four key operation points should be grasped: ① Control the turbidity of the filter effluent to be not more than 0.5NTU to ensure that the manganese dioxide precipitate is fully intercepted; ② If there are reducing interfering substances such as sulfide and ammonia in the raw water, sodium hypochlorite should be added first to remove them to avoid affecting the manganese removal effect; ③ Strengthen the continuous monitoring of manganese content in the raw water, folded plate reaction tank effluent and filter effluent, and feed back the monitoring results in a timely manner to adjust the dosing amount; ④ Ensure that the pH value of the raw water is maintained at 6.5~7.5 (neutral range), so as to ensure that the oxidation reaction can proceed normally and generate manganese dioxide precipitate.

After the implementation of the above measures, the water quality monitoring results showed that the manganese content in the filter effluent of the Phase II water system decreased from 1.10mg/L of raw water to below 0.05mg/L, which met the limit requirement of GB 5749-2022 for manganese content in drinking water. The manganese removal effect was stable and ideal, and no "red water" phenomenon and other secondary water quality problems occurred in the effluent, which realized the safe and stable water supply of the Phase II water system.

4. Conclusions and Recommendations

4.1. Conclusions

(1) The main reason for the excessive manganese in the raw water of Tiechang Reservoir and Yunzhe Reservoir in Cangnan County is the combined effect of local geological conditions and seasonal environmental changes. The reservoir bottom is rich in manganese-containing sediments,

and the high temperature in summer leads to thermal stratification of the reservoir water body and anoxic environment at the bottom, which makes the insoluble tetravalent manganese be reduced to soluble divalent manganese and released into the water body, resulting in a sharp increase of manganese content in the raw water.

(2) Aiming at the different manganese content in the raw water of the two reservoirs, the waterworks adopted targeted manganese removal measures on the basis of the original conventional water treatment process, and achieved ideal manganese removal effects. For the raw water with low divalent manganese content (≤0.32mg/L), the strengthened pre-chlorination process (effective chlorine dosage 0.5mg/L, raw water pH adjusted to 8.5) can effectively oxidize divalent manganese, and the manganese content in the effluent is stably controlled below 0.05mg/L; for the raw water with high divalent manganese content (>0.8mg/L), the method of adding potassium permanganate composite salt (optimal dosage 2.9mg/L) can achieve efficient manganese removal, and the manganese content in the effluent is also reduced to below 0.05mg/L.

(3) The core of chemical oxidation manganese removal technology for waterworks is to oxidize soluble divalent manganese into insoluble tetravalent manganese dioxide precipitate, which is then removed by the conventional coagulation, sedimentation and filtration processes. The key to the selection of oxidant is to adapt to the actual water quality of the waterworks and the existing process conditions. Potassium permanganate and sodium hypochlorite are suitable for the manganese removal transformation of small and medium-sized waterworks with the advantages of simple operation, low cost and quick effect.

(4) Flame atomic absorption spectrophotometry has the advantages of high determination accuracy, good precision and simple operation, which can accurately determine the manganese content in water samples at each treatment stage of the waterworks, and provide reliable data support for the optimization of manganese removal process parameters and the evaluation of manganese removal effect.

4.2. Recommendations

(1) Strengthen the early warning monitoring of raw water quality: The waterworks should establish a long-term monitoring mechanism for the manganese content in the reservoir raw water, especially strengthen the water quality monitoring in summer and autumn when the manganese content is easy to exceed the standard, and master the change law of manganese content in the raw water in time. At the same time, the water intake height of the reservoir should be optimized to avoid taking water from the bottom water body with high manganese content as far as possible.

(2) Optimize the manganese removal process parameters dynamically: The dosage of oxidants (sodium hypochlorite, potassium permanganate composite salt) should be adjusted dynamically according to the real-time change of manganese content in the raw water and the water quality indicators such as pH value and organic matter content, so as to ensure the manganese removal effect and avoid the secondary water quality problems caused by excessive dosage.

(3) Strengthen the daily operation management of the water treatment process: For the filter, the backwashing frequency and backwashing time should be adjusted according to the actual filtration effect to ensure that the filter material is clean and the manganese dioxide precipitate is

fully intercepted; for the chemical dosing system, the accuracy of the metering pump should be checked regularly to ensure the accurate control of the oxidant dosage.

(4) Carry out the research and development of combined manganese removal technology: On the basis of the existing chemical oxidation manganese removal technology, the waterworks can carry out the research and application of combined manganese removal technology such as "oxidation + adsorption" and "biological manganese removal", further improve the manganese removal efficiency and stability, and provide a more diversified technical scheme for the treatment of excessive manganese in raw water.

(5) Strengthen the protection of reservoir water sources: Combined with the local environmental governance, the pollution control of the surrounding areas of the reservoir should be strengthened, the input of manganese-containing pollutants into the reservoir should be reduced, and the ecological environment of the reservoir water source should be improved from the source, so as to reduce the occurrence probability of excessive manganese in the raw water.

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