

Digital Twin-Enabled Governance Modernization and Engineering–Industrial Safety Risk Prevention in a Large-Scale Irrigation District: Evidence and Pathways from the Qinglinghe Irrigation District, China

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Abstract: The digital transformation of large-scale irrigation districts hinges not on the accumulation of devices or three-dimensional visualization, but on restructuring water supply scheduling, engineering maintenance, water-use services, and safety prevention and control systems through real-time data, specialized models, and institutional rules. Employing literature review and case analysis, this paper synthesizes research on digital twins and smart irrigation, draws on materials concerning the modernization of the Qinglinghe Irrigation District and the comprehensive agricultural water price reform, and constructs a five-dimensional analytical framework of “data–model–operations–safety–institutions.” The findings indicate that the district has established foundations in trunk infrastructure, flow measurement facilities, and water rights and pricing mechanisms, yet its development remains constrained by insufficient terminal-level sensing, inconsistent data standards, weak coupling between models and operations, disconnection between safety prevention and digital platforms, and inadequate cross-county coordination and long-term operation and maintenance mechanisms. Accordingly, pathways are proposed in line with demand-driven, layered, and iterative principles: improving integrated sensing and a unified data foundation; prioritizing high-frequency operational applications; establishing human–machine collaborative control together with a tiered closed-loop system for engineering safety prevention; and safeguarding sustained operation through organizational, human-resource, financial, and institutional arrangements. Only when digital twins are embedded in structures of authority and responsibility and in daily operations—while safety is held as the bottom line—can they be translated into genuine irrigation governance capacity.

Keywords: digital twin; Qinglinghe Irrigation District; governance modernization; engineering safety; industrial safety; risk prevention and control

1 Introduction

Large-scale irrigation districts perform multiple functions—safeguarding grain production, allocating water resources, securing engineering works, and delivering public services—and constitute complex governance units linking water source projects, trunk canal systems, and field-level water users. Under the combined pressures of rigid water resource constraints, cropping structure adjustment, and extreme weather risks, operations relying on manual inspection, experience-based allocation, and fragmented ledgers can hardly manage the coordination required across regions, water sources, administrative levels, and stakeholders. Meanwhile, reservoirs, sluices, pumping stations, aqueducts, and other hydraulic structures within irrigation districts operate under water-bearing conditions year-round, and activities such as gate hoisting, pump maintenance, waterside operations, confined-space operations, and flood-season emergency response carry typical industrial safety risk attributes. Once such activities go out of control, they not only damage engineering works but may also endanger downstream flood-control safety and the lives of

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frontline personnel. By connecting physical objects, digital models, and bidirectional data flows, digital twins enable operating states to be continuously sensed, analyzed, and fed back, thereby providing new technical conditions for irrigation governance. Through a systematic review, Jones et al. identified the physical entity, the virtual entity, state measurement, and the physical–virtual connection as the essential elements of a digital twin [1]. Fuller et al. further identified the Internet of Things, artificial intelligence, and data analytics as key enabling technologies, while emphasizing obstacles such as interoperability, data security, and model credibility [2]. In a systematic review of digital twins in safety analysis, risk assessment, and emergency management, Zio and Miqueles demonstrated that digital twins can support the monitoring of complex systems, the implementation of autonomous control, and risk-informed decision-making in accident scenarios, although the twins’ own safety, cybersecurity, and reliability remain open questions [3]. Reviewing the literature on construction safety risk management, Luo et al. categorized applications of digital twins into five areas: real-time monitoring and early warning, safety risk prediction and assessment, accident simulation and emergency response, decision support, and safety training [4]. Accordingly, an irrigation district digital twin cannot be equated with a static digital model or a visualization “single map”; the proper criteria are whether data can update models, whether models can support decision-making, and whether decisions can be fed back into engineering operations—and, further, whether the system can keep engineering conditions and operational risks within acceptable boundaries.

China’s digital twin water conservancy development has formed a relatively explicit policy and technical framework. The Technical Guidelines for Digital Twin Water Conservancy Projects (Trial) propose data foundations, model platforms, and knowledge platforms as supports, and call for strengthening engineering safety, dispatch operations, and the “four forecasts” business—forecasting, early warning, scenario rehearsal, and contingency planning [5]. Irrigation research has gradually shifted from general informatization toward twin-object selection, stereoscopic sensing, model invocation, and automatic control. Xie et al. emphasized that digital irrigation districts constitute the foundation of digital twin irrigation districts and that twin objects should be precisely selected according to operational needs [6]; taking a large Yellow River diversion district as an example, Zhang et al. showed that multi-source information fusion, system applicability, and water allocation are critical to engineering implementation [7]. Nevertheless, existing studies have largely addressed “how to build the platform,” whereas questions such as “what level of maturity can existing engineering and institutions support,” “how technology can be embedded in water rights, water pricing, and engineering maintenance,” and “how engineering and operational risks can be brought under closed-loop control through digital systems” remain insufficiently examined.

The Qinglinghe Irrigation District spans Yao’an and Dayao counties in Chuxiong Prefecture, Yunnan Province. With pronounced topographic relief and widely distributed canal systems, it exhibits the typical constraints of mountainous irrigation districts in Southwest China, while also accumulating experience in continued construction and supporting works, flow measurement, and agricultural water price reform. Taking this district as a case, this paper draws on journal literature, Ministry of Water Resources policies, local government publications, and pilot documents to analyze the foundations, principal constraints, and implementation pathways of its digital twin construction. In this paper, “governance modernization” denotes the coordinated improvement of engineering operations, water allocation, engineering and operational safety, public services, risk control, and accountability mechanisms, rather than the mere pursuit of equipment quantities, model precision, or interface presentation.

2 Literature Review and Analytical Framework

2.1 From digital mapping to physical–virtual closed loop

Digital twins combine continuously updated digital representations with feedback mechanisms. Water-sector research distinguishes information infrastructure, twin platforms, and operational applications, linking monitoring data with models and knowledge bases to support forecasting, early warning, rehearsal, and contingency planning [8]. River-basin research likewise emphasizes integrating observations, coupled models, engineering operations, and governance actors [9]. In irrigation districts, this requires connecting hydraulic infrastructure with spatial and real-time data, engineering records, models, and rules through a “sensing–transmission–computation–decision–execution–evaluation” loop.

2.2 Coordination of data, models, operations, safety, and institutions

Agricultural digital twins vary in maturity. Verdouw et al. distinguished monitoring-based, predictive, prescriptive,

and autonomous management [10], while Pylidianis et al. found that many applications remained conceptual or prototypical, with crop–environment interactions complicating modeling [11]. Alves et al. demonstrated real-time-data-based irrigation prescriptions by integrating IoT platforms and simulation models [12]. However, Yang et al. showed that canal control depends on hydraulic characteristics, gate configurations, and control boundaries; device connectivity alone cannot ensure reliable allocation [13].

Safety research provides relevant approaches. Guo emphasized dynamic identification and tiered responses to coupled construction risks [14]. Gong et al. combined building information modeling, ultra-wideband positioning, and geofencing for personnel-intrusion alerts, reporting a 97.4% comprehensive early warning success rate in deep foundation pit engineering [15]. Li et al. integrated perception, assessment, risk control, and traceability while separating safety and production functions, offering insights for gate and pump control [16]. These applications nevertheless require scrutiny of data quality, model uncertainty, cybersecurity, and liability allocation [3]. Compared with construction safety and individual structures, irrigation districts with extensive canals, open environments, and frequent human–water interaction remain insufficiently studied.

Accordingly, this study develops a “data–model–operations–safety–institutions” framework. Data concerns object identification, continuous sensing, and quality traceability; models concern calibration and uncertainty in hydrology, demand, allocation, hydraulics, structural safety, and risk evolution; operations concern integration into supply planning, scheduling, maintenance, billing, and emergency response. Safety addresses closed-loop hazard identification, warning, interlocking, drills, and incident tracing, while institutions define data ownership, decision authority, operational responsibility, funding, and evaluation. These dimensions are interdependent: unreliable data weaken models, operational disconnection limits their usefulness, and inadequate authorization or safety controls can turn technical failures into engineering damage and casualties. The framework guides the subsequent assessment of Qinglinghe’s construction maturity.

2.3 Technical maturity should serve governance effectiveness

The path toward digital twins progresses from static inventories through real-time monitoring and predictive or prescriptive modeling to physical-system control [1,10]. Each stage requires stronger data continuity, model credibility, and organizational authorization. Maturity targets should therefore reflect operational needs and available capacity: searchable engineering records may suffice initially, critical dispatch points warrant prediction and scenario comparison, and automatic control should begin in suitable canal sections.

Safety applications require stricter validation because false alarms undermine frontline trust and missed alarms may have direct accident consequences [3]. Governance assessment must also consider efficiency, equity, resilience, and accountability. Allocation models should address upstream–downstream delivery disparities and water rights; warning systems should be assessed for accuracy, lead time, false-alarm costs, and practical enforceability; automatic control requires authorization, manual takeover, and fail-safe states. Reported limitations in validation, interoperability, and deployment maturity show that computational capability alone does not establish governance effectiveness [11–12]. This study therefore uses operational usage frequency, decision adoption rate, execution deviation, risk-warning accuracy, and accountability traceability as intermediate indicators connecting technical and governance performance.

3 Foundations for Governance Modernization in the Qinglinghe Irrigation District

3.1 Parallel advancement of trunk engineering and digital upgrading

The Qinglinghe Irrigation District has a designed irrigation area of $30.1 \times 10^4 \text{ km}^2$ (approximately 20,100 ha), spanning Yao’an and Dayao counties. In 2021, the district was included in the national “14th Five-Year Plan” program for the continued construction, supporting works, and modernization of large-scale irrigation districts. The approved scheme planned a total investment of 224.83 million yuan, principally covering a smart water management system, irrigation and drainage trunk and branch canals, flow measurement facilities, and water source projects; upon completion, the program is expected to improve irrigation over an area of $31.2 \times 10^4 \text{ km}^2$ (approximately 20,800 ha) [17]. This implies that digitalization is not a stand-alone undertaking detached from civil works, but proceeds synchronously with canal rehabilitation, metering facilities, and control nodes. Existing informatization pilots, video surveillance, and measurement facilities provide entry points for online monitoring, engineering modeling, and scheduling analysis, and shift the construction focus from “system availability” to legacy equipment integration,

historical data consolidation, and cross-project coordination.

3.2 Water rights and pricing reform as genuine operational demand

In 2023, the Qinglinghe Irrigation District was selected among the first national pilot districts for deepening the comprehensive agricultural water price reform to advance irrigation modernization [18]. Publicly available data show that, based on available water supply, cropping structure, and crop water quotas, the district allocated 64.89 million m³ of water as entitlements to water users; by 2024, the metering rate of trunk works had reached 90% and that below trunk canals 63%, five water user associations (WUAs) had been established, and approximately 37,000 water users participated in the construction and maintenance of water supply facilities [19]. Yao'an County also implements progressive surcharge pricing above quotas: portions exceeding the plan by within 10%, 10–30%, 30–50%, and above 50% are surcharged at 20%, 50%, 100%, and 200%, respectively [20]. Water rights allocation, metered billing, targeted subsidies, and water-saving rewards thus form a continuous operational chain, furnishing the digital platform with application scenarios that are computable, verifiable, and directly relevant to farmers' interests. National development and reform authorities have likewise required improvements in agricultural water metering and water-saving incentive mechanisms [21]. Integrating metering data with water pricing institutions therefore demonstrates governance value more convincingly than adding visualization functions in isolation.

3.3 A quantifiable basis for construction objectives

The district's modernization program has incorporated engineering integrity, metering coverage, irrigation water use, and business application into its objective system. Such indicators delineate verifiable boundaries for the digital twin: platform construction should answer whether it reduces water delivery deviations, shortens emergency response time, raises the effective data rate, and improves service equity, rather than being accepted merely on the number of devices online or the completeness of 3D scenes. Meanwhile, in recent years Yao'an County has taken the agricultural water price reform as its institutional engine, introduced social capital to build high-efficiency water-saving irrigation projects, and combined water rights certificates with differentiated pricing and water-saving rewards [22], indicating that local conditions already support incorporating digital technology, market mechanisms, and community self-governance into irrigation district governance.

3.4 Policy positioning and technical references for engineering safety operation

At the national level, the Ministry of Water Resources has explicitly defined digital twin water conservancy projects as aiming to “ensure the safety of water infrastructure and the full realization of their benefits,” covering the whole life cycle of reservoirs, embankments, sluices, water diversion projects, and irrigation districts, precisely identifying, warning of, and handling risks and their evolution so as to enhance safe, efficient, and sustainable operation; Ye et al.'s systematic review of progress and key issues in digital twin water conservancy construction likewise indicates that engineering safety monitoring and “four forecasts” functions have become standard capabilities of the water conservancy twin system [23]. Niu et al. pointed out that the technical system of intelligent construction for water infrastructure encompasses intelligent sensing, intelligent decision-making and control, and intelligent safety monitoring, and has been implemented and verified in mega-projects such as Wudongde and Baihetan [24]. With respect to the safety of individual structures, Li et al. developed key digital twin-based technologies for dam operation safety covering prediction, early warning, rehearsal, and contingency planning [25]; Zhang et al. applied digital twin technology to the safe operation of the Zaoshi water control project [26]; and Wang et al. proposed an intelligent safety management and control system scheme covering the whole process of hydropower construction and operation [27]. The Qinglinghe Irrigation District possesses reservoir water source projects, trunk and branch canal systems, sluices, pumping stations, and aqueducts; the safety monitoring and video facilities installed synchronously with the modernization works provide the basic conditions for incorporating engineering safety prevention into the digital twin platform. The challenge lies in integrating these single-point technologies into a tiered prevention and control system oriented to canal networks.

4 Principal Constraints on Digital Twin Construction

4.1 The sensing network has not stably extended to the management periphery

Although metering conditions of trunk works continue to improve, real-time information on branch and lateral canals, field pipe networks, and certain water users remains insufficient. In mountainous districts, dispersed monitoring sites, together with communication signal obstruction, lightning strikes, power supply instability, and

sediment, reduce sensor reliability; if terminal data long depend on manual supplementary entry, the platform can hardly distinguish conveyance losses, equipment errors, and actual changes in water demand. The shortcomings of the sensing system therefore lie not only in inadequate site coverage but also in measurement cross-section conditions, equipment calibration, communication availability, and fault handling. Blindly pursuing full coverage would inflate life-cycle costs; site placement should follow decision value, accompanied by assessment of device online rate, effective data rate, and calibration qualification rate.

4.2 Multi-source data lack unified semantics and chains of responsibility

District data are scattered across engineering archives, monitoring terminals, billing systems, inspection records, and the business platforms of the two counties, with inconsistencies in temporal scale, spatial reference, object naming, and coding schemes. Divergences in project construction periods, device protocols, and contractors further create interface barriers. Ouyang et al. divided data standards for irrigation district digital twins into three levels—data classification, naming and coding, and format and content—and emphasized the coordination of basic, monitoring, business management, geospatial, and cross-sector shared data [28]. This conclusion suggests that data governance should not be deferred until after platform completion, but should run through the entire process of equipment procurement, system development, deliverable handover, and engineering acceptance. Unless data custodians, update cycles, and quality rules are specified, objects on the “single map” cannot be stably linked to real-time data, engineering ledgers, and model parameters.

4.3 Model accuracy, operational rules, and risk responsibilities are not yet sufficiently coupled

Current information systems can relatively easily deliver video aggregation, ledger inquiry, and report statistics; by contrast, water-demand forecasting, canal hydraulic simulation, allocation optimization, structural safety assessment, and risk early warning require continuous data, parameter calibration, and explicit scheduling rules. The Qinglinghe Irrigation District features multiple water sources, long-distance conveyance, and complex terrain, so model errors propagate across scales; farmers’ temporary water use, canal silting, and gate execution deviations may likewise invalidate optimal schemes. Models must therefore specify their applicable boundaries, data currency, and error ranges, and incorporate manual review and degraded-operation mechanisms. If algorithmic recommendations are directly equated with administrative decisions, responsibility becomes difficult to apportion once inequitable water delivery or engineering risks materialize, which in turn erodes frontline personnel’s trust in the system.

4.4 Institutional breakpoints in cross-county coordination and long-term operation and maintenance

The district spans two counties: water sources, canal systems, and water users are hydrologically interconnected upstream and downstream, whereas data management, fiscal investment, and grassroots maintenance are divided along administrative boundaries. Absent unified scheduling rules, data-sharing lists, and dispute resolution mechanisms, the platform can only aggregate information and can hardly generate cross-county action. Moreover, software upgrading, base map updating, equipment calibration, model maintenance, and cybersecurity are continuous undertakings whose cost structure differs fundamentally from one-off civil investment. Grassroots personnel are familiar with engineering operation but not necessarily with data analysis, whereas technical personnel are conversant with software yet may be unfamiliar with local allocation conventions. The disconnect between construction-phase acceptance and operation-phase budgeting, knowledge transfer, and service assessment leads to vendor dependence, progressive model degradation, and sluggish fault response.

4.5 Engineering safety prevention has not formed a closed loop with the digital platform

The current state of district safety management is characterized by “human prevention first, technical prevention supplementary”: hazard identification relies on annual inspections and team self-checks; the cycle from hazard discovery, registration, to closure is protracted; high-risk scenarios such as remote gate operation, pumping unit operation, waterside work, and flood-season emergency response lack real-time monitoring, geofencing, and linked contingency plans; and video surveillance mostly serves post-event review, having not been fused with structural safety monitoring or water level and soil moisture data to generate warning rules. More notably, the cybersecurity and functional reliability of the digital twin platform itself have not yet been incorporated into safety prevention—Zio and Miqueles observed that twins may themselves generate new risk sources through data interruption, model distortion, or cyber attacks, and that safety applications must simultaneously weigh the risks and benefits of the twin system [3]. Emergency plans exist largely in textual form, lack digital rehearsals grounded in twin scenarios, and post-incident reviews can rarely trace the monitoring data and operation records at the time. This disconnection between the safety dimension and the data and operations dimensions implies that, even with an information platform in place, the

district cannot yet support the complete prevention chain of “risk identification–monitoring and early warning–linked disposal–traceability and improvement.”

5 Implementation Pathways for Digital Twin-Enabled Governance Modernization

5.1 Determining twin objects and construction tiers by operational value

Operations such as water supply planning, allocation execution, engineering inspection, emergency disposal, metering and settlement, and water user services should first be inventoried and ranked by impact scope, occurrence frequency, data foundation, and decision risk. In the near term, canal headworks, trunk canals, major offtakes, key gates, pumping stations, and vulnerable sections can be designated as core twin units, prioritizing support for water supply planning, real-time allocation, engineering safety, and metering accounting; in the medium term, extension can proceed to branch and lateral canals, field soil moisture, and crop water demand. For each object, a checklist of “object–data–model–operation–safety–responsibility–indicator” should be compiled, with failure modes and safety boundaries of control objects such as gates and pumps registered simultaneously. For objects with unstable data or weak demand, digital ledgers should be established first, without rushing into high-precision three-dimensional modeling. Upgrading maturity through small-scale, verifiable closed loops both contains costs and facilitates the testing of organizational processes.

5.2 Improving integrated “space–air–ground–water–structure” sensing and resilient communication

On the basis of existing measurement and video systems, a site-value assessment should be conducted to distinguish dispatch control points, metering settlement points, engineering safety points, and agricultural water-demand observation points. Trunk cross-sections should first ensure the continuity of water level, flow, and gate position data; key gates should be progressively equipped with integrated monitoring-and-control devices; engineering safety points should add displacement, seepage, cracking, and video-AI behavior recognition items, with differentiated densification for high-fill canal sections, aqueducts, and key structures; at the field level, meteorological, soil moisture, and crop observation points can be deployed in typical areas, complementing full sensor deployment through remote sensing inversion and sample-based extrapolation. Remote sites should adopt optical fiber, mobile communication, or low-power wide-area networks according to terrain, configured with offline caching, breakpoint resumption, and local manual control. All devices should be incorporated into unified asset ledgers, periodic calibration, and fault work orders, so as to avoid “installation without management.”

5.3 Building a unified data foundation and implementing full life-cycle data governance

On the basis of “one map, one object catalog, one set of coding rules,” engineering basic data, geospatial data, real-time monitoring data, business management data, safety management data, and cross-departmental shared data should be integrated. Historical data sources, coordinate references, timestamps, and gaps should first be inventoried and then loaded in batches by quality grade; newly added devices and systems must be delivered in compliance with unified interface, metadata, and coding requirements. A data responsibility matrix should be established, specifying the actors responsible for collection, verification, modification, publication, and archiving, with source labels retained for outliers, manual supplementary entries, and model-generated data. Data involving water users, billing, remote control, and security should be subject to tiered authorization, least-privilege access, and log auditing. Data quality evaluation should be linked with contractor acceptance, management-post performance, and model invocation, so that the data foundation becomes a continuous governance mechanism rather than a one-off data migration.

5.4 Forming minimal model–operation closed loops around high-frequency scenarios

First, the water allocation scenario integrates reservoir available water, canal conveyance capacity, crop water demand, planned water rights, and rotation irrigation rules, comparing schemes in terms of water arrival time, conveyance losses, and upstream–downstream equity. Second, the drought and supply risk scenario rolling-corrects demand on the basis of weather forecasts, soil moisture, and historical water use, informing rationing sequences and the activation of emergency water sources. Third, the engineering safety scenario links inspection, video, gate operating conditions, and key structure monitoring to engineering archives, forming a closed loop of discovery–dispatch–disposal–review; drawing on the dam safety digital twin’s technical route of “prediction–early warning–rehearsal–contingency planning” [25,29], rehearsal comparisons should be conducted for conditions such as water levels above design limits and excessive seepage pressure. Fourth, the water rights and pricing scenario connects plan issuance, metering, settlement, subsidies, rewards, and over-quota surcharges, enabling farmers to query water

use, price basis, and complaint handling. Before deployment, models should be validated through historical process replay and on-site trial operation; after deployment, errors, manual corrections, and execution outcomes should be continuously recorded.

5.5 Establishing human–machine collaborative control and accountability mechanisms

The key distinction between digital twins and conventional information platforms is that computational results can enter actual operation; yet a closed loop does not mean eliminating humans. Pilots can be selected in areas with favorable engineering conditions and complete metering foundations: the platform generates allocation recommendations; dispatchers review them against water conditions, agronomic conditions, and rules, and grant tiered authorization; gates or pumps execute; and outcomes are evaluated using downstream flow, water arrival time, and soil moisture. Low-risk, repetitive operations can be progressively automated, whereas matters involving large-scale supply adjustment, emergency disposal, and billing disputes must retain human decision-making. For every operation, input data versions, model versions, recommended schemes, approvers, execution deviations, and disposal results should be recorded, so as to trace responsibility and calibrate models. Water price reform data should further enhance transparency through public inquiry and WUA participation, preventing the technical system from becoming a new information barrier.

5.6 Constructing a tiered closed loop for engineering and industrial safety prevention

For engineering operation and operational safety, a tiered prevention and control system of equal standing with water allocation should be established. The first tier is risk identification and tiered management and control: hazard inventories, four-color risk zoning maps, and control responsibilities should be incorporated into the twin platform so that risk objects correspond one-to-one with three-dimensional models and monitoring points. The second tier is real-time monitoring and early warning: drawing on the technical route of the deep foundation pit personnel-intrusion warning system—“3D scene + UWB positioning + geofencing” [15]—personnel positioning and boundary-crossing alarms should be implemented for gate and pump maintenance, waterside operations, and confined-space operations, and tiered thresholds with automatic push notifications should be set for conditions such as canal level exceedance, gate jamming, and abnormal seepage pressure. The third tier is linked disposal: upon warning trigger, work orders should be dispatched automatically in accordance with plans, disposed within prescribed time limits, reviewed, and closed; remotely controlled gates and pumps should be equipped with safety interlocks and fail-safe states, ensuring that equipment returns to manually controllable positions when communication is interrupted or models fail. The fourth tier is traceability and improvement: accidents and near-miss events should be digitally reviewed, replaying the data, instructions, and operations at the time to revise models and procedures accordingly. In this process, functional safety thinking should be introduced: notification, interlocking, and shutdown functions bearing on personal and engineering safety should be independently verified, with spurious activation and failure to act distinguished and validated separately [3,16]. Safety prevention models should also serve emergency drills: twin scenarios should simulate canal breach, floods exceeding design standards, and equipment loss of control, testing plan enforceability and personnel response capability and transforming “paper plans” into “scenario-based rehearsals.”

5.7 Aligning organization, talent, funding, and security with long-term performance

Organizationally, the district management agency should take the lead in establishing cross-county scheduling consultation and data-sharing mechanisms spanning Yao'an and Dayao counties, clarifying responsibilities for platform management, engineering control, data review, billing services, and safety disposal. With respect to talent, joint duty by management personnel and technical units, regular training, and post drills should be implemented, incorporating common equipment faults, data quality judgment, model result interpretation, and safety emergency response into competency assessment. With respect to funding, full life-cycle costs should be budgeted beyond the engineering investment, with dedicated lines for communication, calibration, software upgrading, model maintenance, and safety services, and service fees linked to effective data rates, fault repair time limits, and operational performance. With respect to security, boundaries among the business network, control network, and the Internet should be demarcated; remote control should implement two-factor authentication, tiered authorization, backup and recovery, and emergency drills, with the twin system itself incorporated within the scope of security protection. With respect to evaluation, beyond engineering integrity rate, metering rate, irrigation water use coefficient, and application coverage rate, indicators such as effective data rate, model error, scheduling execution deviation, risk-warning accuracy, hazard closure rate, incident closure rate, and water user satisfaction should be added, forming an annual review-and-iteration mechanism.

6 Conclusions

Digital twins offer a technical pathway for the Qinglinghe Irrigation District to connect engineering conditions, water demand, safety risks, and institutional rules in its governance modernization; yet technological effectiveness depends on the degree of coupling with the existing governance structure. The district already possesses foundations in modernization upgrading, flow measurement facilities, water rights and pricing reform, pilot policies, and engineering safety monitoring. The principal contradiction at the current stage has shifted from “whether to build an information system” to “whether a closed loop of mutually reinforcing reliable data, applicable models, daily operations, safety prevention, and accountability institutions can be formed.” Accordingly, adhering to demand-driven principles, layered modeling, human–machine collaboration, and sustained operation and maintenance, verifiable minimal closed loops should first be formed in key canal systems and high-frequency scenarios, with the tiered prevention of engineering and operational safety established as a core business parallel to water allocation, before gradually extending to field-level and cross-departmental operations.

Implementation should further treat pilots as mechanisms of institutional learning: at each stage, data, models, and post-level processes should be tested against real irrigation cycles and safety operation records, with targets, actual values, and deviation causes publicly documented; expansion should proceed only after stability and usage-performance thresholds are met, and where thresholds are not met, basic links should be remediated first. Such an iterative approach of “evaluation–correction–redployment” reduces the path lock-in associated with one-off large investments, and enables fiscal funds, social capital, and grassroots maintenance responsibilities to form mutual constraints around verifiable performance.

For large-scale irrigation districts in mountainous Southwest China, digital twins cannot replicate the equipment density and control modes of plain districts, still less substitute platform completion for governance effectiveness and the safety bottom line. Only by incorporating terrain constraints, grassroots capabilities, farmers’ rights and interests, long-term costs, and engineering safety into technical solutions—and by testing against improvements in water delivery equity, water-saving efficiency, engineering safety, operational safety, and public services—can digital twins be transformed from project-based information tools into sustainable governance infrastructure. This study principally conducts a normative analysis based on publicly available materials and case documents; subsequent research should exploit continuous operational data to perform before-and-after comparisons of allocation deviations, model accuracy, operation and maintenance costs, risk-warning accuracy, and user satisfaction, so as to further verify the actual performance of the proposed pathways.

References

- [1] Jones D, Snider C, Nassehi A, et al. “Characterising the Digital Twin: A systematic literature review”[J]. *CIRP Journal of Manufacturing Science and Technology*, 2020, 29: 36-52. <https://doi.org/10.1016/j.cirpj.2020.02.002>.
- [2] Fuller A, Fan Z, Day C, et al. “Digital Twin: Enabling Technologies, Challenges and Open Research”[J]. *IEEE Access*, 2020, 8: 108952-108971. <https://doi.org/10.1109/ACCESS.2020.2998358>.
- [3] Zio E, Miqueles L. “Digital twins in safety analysis, Risk Assessment and Emergency Management”[J]. *Reliability Engineering & System Safety*, 2024, 246110040. <https://doi.org/10.1016/j.ress.2024.110040>.
- [4] Luo Q, Sun C, Li Y, et al. “Applications of digital twin technology in construction safety risk management: a literature review”[J]. *Engineering, Construction and Architectural Management*, 2025, 32(6): 3587-3607. <https://doi.org/10.1108/ECAM-11-2023-1095>.
- [5] Zhan Quanzhong, Chen Zhenxuan, Zhang Chao, et al. “Analysis of the Technical Guidelines for Digital Twin Water Conservancy Engineering Construction (Trial)”[J]. *Water Conservancy Informatization*, 2022,(4):1-5. <https://doi.org/10.19364/j.1674-9405.2022.04.001>.
- [6] Xie Chongbao, Bai Jing, Zheng Shizong, et al. “Discussion on the core essentials and key technologies of digital twin irrigation district construction”[J]. *China Rural Water and Hydropower*, 2024(11): 179-184+195.
- [7] Zhang Yu, Bian Xiaonan, Zhang Hongliang, et al. “Research on the application prospects of digital twin technology in large-scale irrigation districts”[J]. *Journal of Irrigation and Drainage*, 2022, 41(S2): 71-76. <https://doi.org/10.13522/j.cnki.ggps.2022581>.
- [8] Sun Yuling, Jin Youjie, Liu Yan. “Review of digital twin water conservancy technology architecture and

- application practices”[J]. *Water Resources Informatization*, 2026(1): 1-7+27. <https://doi.org/10.19364/j.1674-9405.2026.01.001>.
- [9] Yang Yifang, Xie Chen, Fan Ziwu, et al. “Digital twinning of river basins towards full-scale, sustainable and equitable water management and disaster mitigation”[J]. *npj Natural Hazards*, 2024,1 (1): 43-43. <https://doi.org/10.1038/s44304-024-00047-2>.
- [10] Verdouw C, Tekinerdogan B, Beulens A, et al. “Digital twins in smart farming”[J]. *Agricultural Systems*, 2021, 189. <https://doi.org/10.1016/j.agry.2020.103046>.
- [11] Christos P, Sjoukje O, N. I A. “Introducing digital twins to agriculture”[J]. *Computers and Electronics in Agriculture*, 2021, 184. <https://doi.org/10.1016/J.COMPAG.2020.105942>.
- [12] Gomes R A, Filev R M, Fábio L. “Development of a Digital Twin for smart farming: Irrigation management system for water saving”[J]. *Journal of Cleaner Production*, 2023, 388. <https://doi.org/10.1016/J.JCLEPRO.2023.135920>.
- [13] Yang Zhigang, Wang Zhongjing, Liu Jinlong, et al. “Canal Controllability Identification Based on Automation Theory to Improve Water Delivery Efficiency in Irrigation Canal Systems”[J]. *Journal of Irrigation and Drainage Engineering*, 2023, 149(8). [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0001742](https://doi.org/10.1061/(ASCE)IR.1943-4774.0001742).
- [14] Guo Feng. “Analysis of the coupling relationships of construction safety risks based on digital twin”[J]. *Construction Technology*, 2024, 53(10): 138-142.
- [15] Gong Peisong, Shen Xinyun, Han Bowen, et al. “Digital twin system for early warning of personnel area-intrusion behaviors in deep foundation pit engineering”[J]. *China Safety Science Journal*, 2025, 35(8): 33-39. <https://doi.org/10.16265/j.cnki.issn1003-3033.2025.08.1471>.
- [16] Li Hao, Liu Gen, Wen Xiaoyu, et al. “Industrial safety control architecture and key technologies of digital twin systems for human-machine interaction”[J]. *Computer Integrated Manufacturing Systems*, 2021, 27(2): 374-389. <https://doi.org/10.13196/j.cims.2021.02.006>.
- [17] Yunnan Provincial Department of Water Resources. “The Chuxiong Qinglinghe Irrigation District becomes one of the three districts in Yunnan Province listed in the national “14th Five-Year Plan” program for modernization of large-scale irrigation districts”[EB/OL]. (2021-07-02)[2026-08-08]. <https://wcb.yn.gov.cn/irs-c-web/search.shtml?code=198dfc140bb&dataTypeId=558&searchWord=%E8%9C%BB%E8%9B%89%E6%B2%B3%E7%81%8C%E5%8C%BA>
- [18] General Office of the Ministry of Water Resources. “Notice on publishing the first batch of pilot districts for deepening the comprehensive agricultural water price reform to promote irrigation modernization”[EB/OL]. (2023-04-28)[2026-08-08]. http://www.mwr.gov.cn/zwgk/gknr/202510/t20251001_2080881.html.
- [19] Li Xiaoqing. “With ‘clear and accounted water’, industries gain momentum”[N]. *People’s Daily*, 2024-12-20(017). <https://doi.org/10.28655/n.cnki.nrmrb.2024.016320>.
- [20] Yao'an County Development and Reform Bureau. “Notice of Yao'an County on implementing progressive surcharge pricing for agricultural water exceeding quotas (Trial)”[EB/OL]. (2023-07-28)[2026-08-08]. <https://yaoan.gov.cn/info/5133/329064.htm>.
- [21] National Development and Reform Commission. “Notice on deepening the comprehensive agricultural water price reform”[EB/OL]. (2021-07-02)[2026-08-08]. https://www.ndrc.gov.cn/xwdt/tzgg/202107/t20210716_1290565.html
- [22] Yunnan Provincial Department of Water Resources. “Entering Yunnan: exploring the deepening path of water conservancy reform”[EB/OL]. (2026-06-06)[2026-08-08]. <https://wcb.yn.gov.cn/irs-c-web/search.shtml?code=198dfc140bb&dataTypeId=558&searchWord=%E8%B5%B0%E8%BF%9B%E4%BA%91%E5%8D%97%E5%BC%8C%E6%8E%A2%E8%AE%BF%E6%B0%B4%E5%88%A9%E6%94%B9%E9%9D%A9%E7%9A%84%E6%B7%B1%E5%8C%96%E8%B7%AF%E5%BE%84>
- [23] Ye Yuntao, Jiang Yunzhong, Kou Huaizhong. “Progress, key issues, and countermeasures of digital twin water conservancy construction”[J]. *China Water Resources*, 2026(5): 36-45.
- [24] Niu Xinqiang, Xie Mingxia, Xu Lifu. “Theoretical reflections and development prospects of intelligent construction of water conservancy projects”[J]. *Strategic Study of CAE*, 2026, 28(3): 265-282.
- [25] Li Yongsheng, Yu Jun, Li Yinan, et al. “Research and application of key digital twin-based technologies for dam operation safety covering prediction, early warning, rehearsal, and contingency planning”[J]. *Water Resources*

- Technical Supervision, 2025(12): 34-37+73.
- [26] Zhang Jiade, Liu Maosheng, Li Kun, et al. "Application of digital twin technology to the safe operation of the Zaoshi Water Control Project"[J]. Dam and Safety, 2025(5): 23-27.
- [27] Wang Junsong, Duan Bin, Wu Wanbo, et al. "Research on the construction scheme of an intelligent safety management and control system for hydropower projects"[J]. China Safety Science Journal, 2021, 31(S1): 96-102. <https://doi.org/10.16265/j.cnki.issn1003-3033.2021.S1.018>.
- [28] Ooyang Jun, Liu Chao, He Peiting, et al. "Research on data standardization for irrigation district digital twin engineering"[J]. Yangtze River, 2026, 57(6): 268-276. <https://doi.org/10.16232/j.cnki.1001-4179.2026.06.030>.
- [29] Shao Chengfei, Zheng Sen, Xu Yanxin, et al. "A visualization system for dam safety monitoring with application of digital twin platform"[J].Expert Systems With Applications,2025,271126740-126740. <https://doi.org/10.1016/J.ESWA.2025.126740>.

