

DIGITAL INTELLIGENCE-DRIVEN INNOVATION AND PRACTICE FOR WATER RESOURCE MANAGEMENT IN IRRIGATION DISTRICTS

INNOVATION ET PRATIQUES GUIDEES PAR L'INTELLIGENCE NUMERIQUE POUR LA GESTION DES RESSOURCES EN EAU DANS LES PERIMETRES IRRIGUES

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ABSTRACT

Against the backdrop of global climate change, extreme hydrological events such as droughts and floods occur frequently, exacerbating the uneven spatial and temporal distribution of freshwater resources. Agricultural irrigation, as the largest consumer of global freshwater resources, faces the dual pressures of increasing uncertainty in water supply and growing water demand. Improving agricultural water use efficiency and implementing refined irrigation system management have become a global consensus and common action to ensure food security and promote sustainable agriculture. Digital intelligence technologies, represented by digital twin, Internet of Things (IoT) and big data, have provided a brand-new technical path for innovating water resource management methods in irrigation districts. The construction of digital twin irrigation districts has emerged as a key approach to achieving precise monitoring, intelligent scheduling and efficient management of irrigation water resources. Based on global trends in agricultural water resource management and combined with China's pioneering pilot practices in digital twin irrigation districts, this paper systematically elaborates the technical framework and implementation principles of irrigation district water resource management supported by digital intelligence. It summarizes practical achievements including the improvement of information infrastructure, integrated application of water conservancy models, and enhancement of irrigation and drainage services. The paper also analyzes existing challenges such as inadequate data sharing mechanisms, insufficient technical scenario adaptation, and shortage of professional talents, and proposes corresponding optimization countermeasures. These findings can provide practical references for the digital transformation of water resource management in irrigation districts worldwide.

Keywords: Digital Twin; Irrigation District; Digital Intelligence; Irrigation Water Resources Management.

RÉSUMÉ

Dans le contexte du changement climatique mondial, les phénomènes hydrologiques extrêmes, tels que les sécheresses et les inondations, surviennent fréquemment et aggravent la répartition inégale des ressources en eau douce dans l'espace et dans le temps. L'irrigation agricole, qui constitue le principal usage des ressources mondiales en eau douce, subit la double pression d'une incertitude croissante de l'approvisionnement en eau et d'une demande en hausse. Améliorer l'efficacité d'utilisation de l'eau en agriculture et mettre en œuvre une gestion fine des systèmes d'irrigation sont devenus un consensus mondial et une action commune pour garantir la sécurité alimentaire et promouvoir une agriculture durable. Les technologies d'intelligence numérique, représentées par le

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jumeau numérique, l'Internet des objets (IoT) et les mégadonnées, ouvrent une voie technique entièrement nouvelle pour faire évoluer les méthodes de gestion des ressources en eau dans les périmètres irrigués. La création de périmètres irrigués à jumeau numérique est devenue une approche essentielle pour assurer un suivi précis, une programmation intelligente et une gestion efficace des ressources en eau d'irrigation. En s'appuyant sur les tendances mondiales de la gestion de l'eau agricole et sur les pratiques pilotes innovantes menées en Chine dans les périmètres irrigués à jumeau numérique, cet article expose systématiquement le cadre technique et les principes de mise en œuvre d'une gestion des ressources en eau des périmètres irrigués soutenue par l'intelligence numérique. Il résume les résultats pratiques obtenus, notamment l'amélioration des infrastructures d'information, l'application intégrée de modèles hydrauliques et le renforcement des services d'irrigation et de drainage. L'article analyse également les difficultés existantes, telles que l'insuffisance des mécanismes de partage des données, l'adaptation limitée des technologies aux scénarios d'usage et la pénurie de professionnels qualifiés, puis propose des mesures d'optimisation correspondantes. Ces résultats peuvent fournir des références pratiques pour la transformation numérique de la gestion des ressources en eau dans les périmètres irrigués du monde entier.

Mots-clés : Digital Twin; Périmètres irrigués; Intelligence numérique; Gestion des ressources en eau d'irrigation.

1. INTRODUCTION

Global climate change has significantly increased the frequency and intensity of extreme events such as droughts, floods and heatwaves by altering the hydrological cycle and reshaping the spatial and temporal distribution of regional water resources. This has posed persistent challenges to the stability of agricultural water supply and the safe operation of irrigation systems. Irrigation water accounts for more than 70% of total global freshwater consumption. With global population growth, rising food demand and intensifying climate change, traditional irrigation districts relying on manual inspections, experience-based scheduling and extensive water distribution can no longer meet the current requirements for efficient water resource utilization, precise irrigation system control and food security. Promoting efficient utilization of agricultural water resources and realizing digital and intelligent upgrading of irrigation district management have become important measures to address the water crisis, ensure food supply and promote sustainable agricultural development.

As a large agricultural country with severe water scarcity, China's per capita water resources are only one-quarter of the world average. Irrigation water has long accounted for more than 60% of the country's total water consumption. The efficiency and management level of water resource allocation in irrigation districts are directly related to national food security, ecological security and water resources security. Affected by climate change and uneven spatial and temporal distribution of water resources, irrigation districts in China generally face practical problems such as resource-based water shortage, seasonal water shortage and low irrigation water use efficiency. Traditional management methods have shortcomings including insufficient monitoring coverage, lagging data collection, highly subjective decision-making and rough water measurement. Some existing information systems suffer from fragmentation, isolation and low integration, making it impossible to achieve precise control and intelligent scheduling throughout the entire water resource process. Digital intelligence technology with digital twin as the core provides a feasible technical solution to these irrigation district management problems and improves water resource allocation efficiency by constructing an integrated management system featuring synchronous mapping, real-time interaction and dynamic regulation between physical irrigation districts and digital models. In recent years, China has promoted pilot projects of digital twin irrigation districts and explored practical paths for the deep integration of digital intelligence technology and irrigation district water resource management, achieving certain results. Based on this, this paper combines domestic pilot practices to systematically sort out the construction content and practical results of water resource management in digital intelligence irrigation districts, analyzes existing problems and proposes optimization countermeasures. This aims to provide support

for the modernization transformation of China's irrigation districts and also offer practical experience for similar irrigation districts worldwide.

2. CONTENT AND NECESSITY OF DIGITAL TWIN IRRIGATION DISTRICT CONSTRUCTION

2.1 Overview of digital twin irrigation district construction

In 2021, the Ministry of Water Resources issued the Guiding Opinions on Vigorously Promoting the Construction of Smart Water Conservancy, Top-level Design of Smart Water Conservancy Construction and 14th Five-Year Plan for Smart Water Conservancy Construction, clarifying the goals of smart water conservancy construction. In accordance with the general requirements of "demand-driven, application-first, digital empowerment and capacity improvement", the construction of digital twin basins, digital twin water networks and digital twin projects is coordinated. Efforts are continuously made to improve the construction of intelligent water conservancy business application systems and build a digital twin water conservancy system with forecasting, early warning, rehearsal and plan functions.

Digital twin irrigation districts are an important component of smart water conservancy construction and a key means to improve water resource utilization efficiency. They are also an important measure to enhance irrigation district management capacity and grain production capacity, as well as a crucial path to promote irrigation district modernization. In 2022, the Ministry of Water Resources issued the *Technical Guidelines for the Construction of Digital Twin Irrigation Districts*, which clearly states that digital twin irrigation district construction takes the physical irrigation district as the unit, spatiotemporal data as the foundation, mathematical models as the core, and water conservancy knowledge as the driving force. It digitally maps, intelligently simulates and prospectively rehearses all elements and the entire process of construction and operation of the physical irrigation district, operates synchronously with the physical irrigation district, and achieves virtual-real interaction and iterative optimization. It is a new type of infrastructure that can realize real-time monitoring of the physical irrigation district, timely problem identification and continuous scheduling optimization.

Due to the complex types and diverse functions of irrigation districts, they possess multiple characteristics of watersheds, water networks and water conservancy projects. Meanwhile, the current information infrastructure of large and medium-sized irrigation districts is generally underdeveloped, and the coverage and accuracy of water regime and engineering monitoring data in irrigation districts remain low. The construction of digital twin irrigation districts is still in its infancy. Therefore, following the principles of overall planning, prioritizing urgent needs and implementing step by step, the Ministry of Water Resources selected 49 large and medium-sized irrigation districts with high local enthusiasm, urgent demand, good water supply and management foundation, and typical demonstration significance to carry out pilot construction in 2022. The construction of digital twin irrigation districts is planned to be completed within 2-3 years, with expected breakthroughs in promoting business collaboration, innovating work methods and improving service efficiency. A batch of replicable and scalable application results will be formed to drive the effective, orderly and efficient advancement of digital twin irrigation district construction across China, providing solid support and strong impetus for the high-quality development of irrigation districts in the new stage.

2.2 Architecture of the digital twin irrigation district

The construction of digital twin irrigation districts includes five components: information infrastructure, digital twin platform, business application platform, cybersecurity system, and operation and maintenance system. The overall architecture of the digital twin irrigation district is shown in Figure 1.

The construction of digital twin irrigation districts requires the establishment of a comprehensive perception network covering all elements. By integrating the distribution of water sources, canal and field layout of the irrigation district, an integrated monitoring system combining space, ground and underground elements should be constructed. Water level, flow and rainfall monitoring equipment should be installed at water source projects such as reservoirs and pumping stations. Along main and branch canals, devices for monitoring canal water level, flow, gate operation status and video surveillance should be deployed. Soil moisture, meteorological conditions and crop growth monitoring terminals should be set up in the fields. Smart metering facilities should be popularized at the user end to achieve full coverage and real-time collection of key information in the irrigation district, providing a basis for data application and decision analysis.

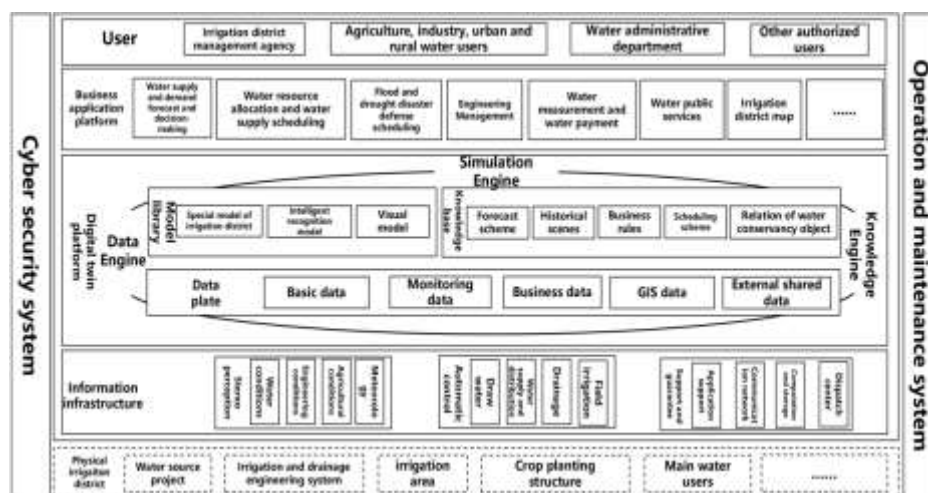


Figure 1. Architecture of the digital twin irrigation district

The data platform is the core of the digital twin irrigation district. Building a data platform requires integrating and accessing real-time monitoring data, engineering data, hydrological and meteorological data, water management data, geographic information data and other data sources. Unified data standards and governance processes should be established to complete data cleaning, calibration, storage and sharing. By building a unified data platform, information silos between various business systems are broken, realizing unified data management and multi-party calling, avoiding problems such as repeated collection and data inconsistency, and providing stable data support for model calculation and system application.

The model library is the key to realizing intelligent decision-making. It is necessary to build a model system adapted to local conditions around the core businesses of the irrigation district, including water supply forecasting models, canal hydrodynamic models, crop water demand models, optimal scheduling models, intelligent identification models, etc. Through field data calibration and model verification, these models can accurately simulate the entire process of water supply, conveyance and distribution in the irrigation district. They provide a quantitative basis for inflow forecasting, water demand calculation, water distribution scheme generation and emergency dispatching judgment, enabling scheduling decisions to shift from "experience-driven" to "data-driven".

The construction of the business application platform focuses on irrigation district management and farmer service needs. Practical functions such as water supply and demand forecasting and decision-making, intelligent scheduling, water rights management, irrigation services and project operation and maintenance should be developed. Through the system, functions such as remote control of gates and pumping stations, automatic water distribution scheduling, online water use application, intelligent

water fee settlement and operation and maintenance order distribution are realized. Traditional offline management processes are transferred online, simplifying procedures and improving management and service efficiency. At the same time, a cybersecurity and data security protection system needs to be established, and the operation and maintenance management system should be improved. Responsibilities and personnel allocation for operation and maintenance should be clearly defined to ensure the long-term stable operation of facilities and platforms.

3. ACHIEVEMENTS OF DIGITAL TWIN IRRIGATION DISTRICT PILOT WORK

Through nearly three years of pilot work on digital twin irrigation districts, the application effects of digital intelligence technology in pilot irrigation districts have gradually emerged, promoting the transformation of irrigation district management modes from traditional manual to digital intelligence.

3.1 *Significant improvement in monitoring and perception capabilities*

Digital twin irrigation district construction has prioritized improving the foundation for calculation, adhering to the principle of "integrating existing facilities, coordinating new construction, and standardizing new installations". By applying new technologies such as remote sensing and artificial intelligence, an integrated "space-ground-underground" monitoring and perception system for irrigation districts has been systematically constructed. A total of more than 38,000 sets of sensing equipment have been installed in the pilot irrigation districts, comprehensively improving the efficient acquisition capability of key element information in irrigation districts and enhancing the high-precision, high-frequency and continuous response capability of mathematical model calculations.

First, the first batch of pilot irrigation districts fully excavated and integrated existing information construction results, maximizing the effectiveness of built equipment and data platforms. The Weishan Irrigation District in Shandong Province fully integrated previous project construction results, incorporating 1,052 video surveillance systems, 11 large-scale gate remote control facilities, 39 water diversion gate remote control facilities and 13 sets of upgraded flow measurement equipment into the digital twin irrigation district platform. This effectively solved the problem of system incompatibility between different equipment manufacturers and saved approximately 2.6 million yuan (around 0.4 million dollars) in funds.

Second, pilot irrigation districts actively promoted cross-sectoral and cross-level data collaboration, establishing stable and efficient data sharing mechanisms with meteorological, agricultural and rural affairs departments. The Zhanghe Irrigation District in Hubei Province accessed data from 301 hydrological stations of the water resources department, 9 meteorological stations of the meteorological department and 6 water quality monitoring stations of the environmental protection department. This enabled the irrigation district to comprehensively grasp information such as water regime, rainfall and water quality, providing a scientific basis for water resource scheduling and flood and drought disaster prevention.

In addition, more than 3,100 new water regime monitoring stations, over 460 agricultural condition monitoring stations, more than 1,100 engineering condition monitoring stations, over 190 meteorological stations and more than 3,800 video monitoring surveillances were built in the first batch of digital twin pilot irrigation districts. Combining "upgrading old facilities", "sharing data" and "building new installations", an information perception network covering water regime, engineering conditions, agricultural conditions, meteorology and other factors in the irrigation district has been formed, providing a data foundation for business digitization and decision-making intelligence.

3.2 *Establishment of whole-process models to support scientific decision-making*

Digital twin pilot irrigation districts have focused on constructing professional irrigation district models such as inflow forecasting, water demand forecasting and water allocation. A total of more than 160 water conservancy thematic models, mainly based on mechanism models and supplemented by mathematical statistics models, have been developed, forming typical scenario applications. Through field application, technical verification, iterative upgrading and continuous integration with business needs, high fidelity between mathematical simulation processes and physical processes has been ensured, realizing the effective connection from data to model to decision-making.

In terms of water demand prediction, remote sensing technology was used to extract crop planting structures, perceive crop water demand information and invert soil moisture in 29 pilot irrigation districts. The Pishihang Irrigation District in Anhui Province used Sentinel series satellite remote sensing data to dynamically interpret crop planting structures, soil moisture and water surface. Through the construction of the digital twin system, in 2025, when the rice planting area was basically the same as in 2024 and rainfall was 5% less than the same period in 2024, irrigation water usage was reduced by 310 million cubic meters compared with 2024, with direct economic benefits from water resource savings amounting to 72 million yuan(around 10 million dollars).

In terms of water supply and demand balance, the Qinglongshan Irrigation District in Heilongjiang Province constructed a joint scheduling model for groundwater, surface water and rainwater resources. In 2025, in response to local drought caused by continuous high temperature and little rain in summer, the water allocation scheme was rapidly updated through real-time data analysis and model prediction. Compared with the traditional static scheme based on historical experience, this avoided water shortage risks for approximately 20% of farmland.

In terms of water allocation, through the construction of the digital twin irrigation district, the Santunhe Irrigation District in Xinjiang integrated data from 97 water regime monitoring stations and 12 mountain rainfall automatic monitoring stations. The water allocation model was applied in the irrigation district to automatically generate the optimal water allocation scheme according to real-time water regime, rainfall and other information. Through model application, the time required to formulate water distribution plans was shortened from 2 hours to 20 minutes, increasing water distribution efficiency by 75%.

In terms of energy saving and consumption reduction, the Dayudu Irrigation District in Shanxi Province adopted a system optimization method to coordinate pumping stations in groups. The objective function was set as the highest total operating efficiency and lowest total energy consumption cost of the pumping station group, with the start-stop status and operation combination of each pumping station as decision variables, and regional safety water levels, actual water demand and power grid load as constraints. Through the application of the pumping station group scheduling decision model, each unit saved 11,000 kWh of electricity after 24 hours of operation.

3.3 *More accurate and efficient irrigation services*

On the one hand, the risk prevention and control mechanism has shifted from post-emergency response to pre-warning and rehearsal. The Zhanghe Irrigation District in Hubei Province optimized flood discharge decisions through flood routing simulation, solving the problems of insufficient quantitative analysis for drought prevention and low flood forecasting accuracy. The flood and drought disaster prevention module realizes 72-hour early warning of rainfall and water conditions. Since 2023, it has successfully coped with multiple heavy rainfall processes, avoiding inundation of 12,000 mu of farmland and reducing economic losses by 45 million yuan(around 6.4 million dollars). The Ouyanghai Irrigation District in Hunan Province constructed video intelligent recognition models for floating object detection, personnel intrusion detection, slope collapse detection and channel crack detection. Combined with UAV inspection and manual inspection, a three-dimensional inspection system was

established. In 2024, a total of 6 channel landslide hidden dangers and 13 illegal intrusion incidents were discovered. Timely warning and disposal effectively prevented the occurrence of safety accidents.

On the other hand, the water supply service model has shifted from "management-led" to "demand-driven". The Tongshanyuan Irrigation District in Zhejiang Province built a user-oriented mobile application, allowing farmers to submit water demand online through the app. Based on the irrigation prediction model and supply and demand balance analysis, the digital twin system automatically generates water distribution scheduling schemes and feeds back water release plans to users. The Doufuwo Irrigation District in Shandong Province realized management and analysis of data from 1,780 wells using the digital twin platform. The development of a mobile phone app extends services to the field, providing farmers with irrigation water suggestions, remote control of well switches and reporting of irrigation equipment maintenance problems, effectively supporting efficient water-saving irrigation in the field.

4. Difficulties and Challenges

4.1 *Inadequate data sharing mechanisms*

In some regions, inter-departmental cooperation mechanisms are not perfect, and data standards among water conservancy, agriculture, meteorology, hydrology and other departments are not uniform. Cross-sectoral and cross-level data sharing lacks institutional guarantees and technical support, making it difficult to break down data barriers. Multi-source data cannot be effectively integrated. Key data such as agricultural conditions and meteorology are difficult to obtain in many irrigation districts, forcing them to build their own soil moisture monitoring stations, weather stations and other facilities.

This not only causes repeated investment and waste of funds but also makes it difficult to guarantee the accuracy and timeliness of data. The data collection process in some irrigation districts is not standardized, resulting in uneven data quality with many missing values and outliers, reducing data availability. This has affected the precise allocation and scientific management of water resources in digital twin irrigation districts, preventing the full exploitation of data value.

4.2 *Insufficient technical scenario adaptation*

The market has insufficient investment in the research and development of products and equipment for irrigation district informatization construction. There are limited types of hardware products and equipment with production licenses and product quality certifications. A sound production license and quality certification system has not yet been formed, and a mature product series has not been established. Besides, there is a low level of repeated development in business application systems, and a lack of mature and professional software suitable for irrigation district businesses.

Although the Ministry of Water Resources has issued some recommended lists of digital twin irrigation district models, some irrigation districts still have deficiencies in model construction and lack accurate models adapted to their own characteristics. Most of the hardware equipment used in irrigation districts is transplanted from other industries, which cannot meet the actual needs of digital twin irrigation district construction in terms of adaptability and cost-effectiveness.

4.3 *Shortage of professional talent teams*

The existing talent teams in irrigation districts have difficulty meeting the construction needs of digital twin irrigation districts. The construction and operation of digital twin irrigation districts require compound talents with expertise in multiple fields such as water conservancy, automatic control and information technology. However, the current technical talent structure in irrigation districts is

unreasonable, with a prominent shortage of information technology-related talents. Most existing personnel in irrigation districts are non-information technology professionals who can only meet the basic operation requirements of daily management. More complex application and maintenance work still relies on external technical support. With the expansion of the construction scale of digital twin systems, problems in operation, management and maintenance have become increasingly prominent, affecting the stable operation and functional performance of the systems.

5. Recommendations for Countermeasures

5.1 *Improve data sharing mechanisms*

Promote cooperation among water conservancy, agriculture, meteorology, aerospace information and other departments to jointly formulate data sharing agreements. Clarify the boundaries of data rights and responsibilities and sharing rules, and establish standardized data interface specifications. Relying on water conservancy cloud or government cloud resources, secure data sharing is realized through hierarchical authority management. Strengthen data security management and increase the application of technologies such as encrypted transmission. Combined with blockchain technology, record data flow traces to ensure data privacy and security.

5.2 *Strengthen research and development and adaptation of key technologies*

Organize scientific research and joint research on key technical problems restricting the development of digital twin irrigation districts. On the basis of in-depth investigation, take effective measures to promote the transformation of existing scientific research results into production practice, providing strong technical support for the construction of digital twin irrigation districts in China. Strengthen market guidance and encourage specialized companies to invest in the development of professional hardware equipment and software systems for digital twin irrigation district construction, improving product adaptability and cost-effectiveness.

5.3 *Cultivate professional talent echelons*

Implement "order-based" talent training to cultivate compound talents targeted according to the actual needs of irrigation districts. Optimize personnel structure and improve personnel quality. In practical work, allow irrigation district technical personnel to participate in the entire process of planning, design, development, commissioning and operation of information construction projects to comprehensively improve their capabilities. Establish and improve talent incentive mechanisms and create a good environment for information technology talents. Gradually establish a backbone team proficient in mastering and applying information technology to meet the needs of the continuous advancement and deepening of digital twin irrigation district construction.

6. Conclusion

Against the background of global climate change, efficient utilization of agricultural water resources and scientific irrigation district management have become the common pursuit of the international community. Digital twin technology provides core support for achieving this goal, and the construction of digital twin irrigation districts is the key path for the modernization transformation of irrigation districts. China's digital twin irrigation districts have achieved remarkable results, with leaps and bounds in information infrastructure, water conservancy model application and irrigation and drainage service efficiency. However, they still face practical challenges in data sharing, technology adaptation, talents and other aspects.

In the future, the digital intelligence construction of irrigation districts should be based on the development trend of global agricultural water resources management, adhering to the principles of water conservation priority, practical orientation, adaptation to local conditions and long-term operation

and maintenance. Taking data integration as the foundation, technological innovation as the driving force, financial security as the support and talents as the guarantee, we will continue to promote the deep integration of digital intelligence technology and irrigation water resource management. By optimizing the construction path, a modern irrigation district management system with all-factor monitoring, all-data support and all-intelligent control will be constructed, comprehensively improving water resource utilization efficiency and management efficiency. This will not only provide solid support for China to ensure food security but also provide Chinese solutions and practical references for the digital and intelligent transformation of irrigation districts worldwide.

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