Research on Water Resource Management in Yellow River Irrigation Areas Based on Digital Twins

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Abstract. With the swift progress of information technology, the deployment of digital twin technology in water resources management within the Yellow River Irrigation District (YRID) demonstrates considerable promise. This study seeks to investigate the effectiveness of digital twin technology in addressing issues such as water scarcity, the imbalance between supply and demand, insufficient scientific data support and intelligent decision-making systems, as well as the challenges associated with water fee collection and management. By developing a digital twin model, accurate simulation, efficient data analysis, and intelligent decision support for the water resources in YRID were achieved, significantly enhancing the scientific basis and accuracy of water resource management. The findings indicate that the implementation of digital twin technology can lead to approximately a 15% reduction in water resource waste, a 20% improvement in water resource utilization efficiency, and optimization of the water fee collection and management processes to lower overall management costs. These outcomes not only offer innovative solutions for water resource management in the Yellow River Irrigation District but also provide valuable lessons for managing water resources in other irrigation areas.

Keywords: Digital twin technology; Yellow River Irrigation Area; water resources management

1 Introduction

As an important agricultural production base in China, the efficiency and effectiveness of water resources management in the irrigation area is directly related to the stability and sustainable development of agricultural production[1]. However, the traditional water resource management relies on empirical judgment and manual operation, and lacks scientific data support and intelligent decision-making system, which leads to inefficient utilization of water resources, high management costs and increased pressure on the ecological environment[2][3][4].

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The main objective of this study is to explore the application of digital twin technology in water resource management in the diversion of yellow irrigation areas, and to evaluate its practical effects in improving the efficiency of water resource utilization and optimizing the water fee collection and management process. The novelty of the study lies in the fact that we have not only constructed a virtual system corresponding to the actual diversion and irrigation area to achieve real-time monitoring, precise analysis and optimal scheduling of the actual system, but also quantified the specific contribution of digital twin technology in water resources management through empirical studies[5][6]. Furthermore, this research underscores the innovative utilization of digital twin technology within the realm of water resource management. It encompasses sophisticated simulation and prediction capabilities, streamlined data analysis, and advanced decision support systems. These advancements present new methodologies and fresh insights for managing water resources not only in the Yellow River irrigation districts but also in broader contexts. Figure 1 delineates the intricate connections between the various components of the digital twin framework.

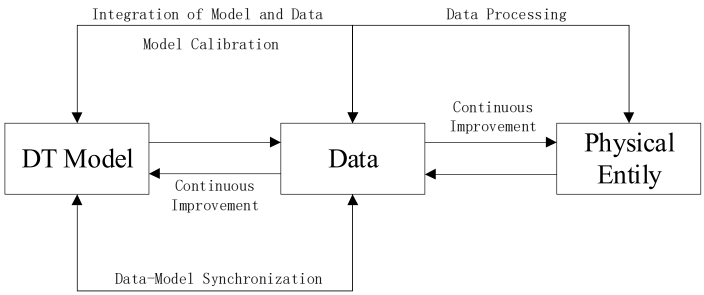

Fig. 1. The interrelationship between multiple aspects of a digital twin

2 Problems Existing in Water Resources Management in the Yellow River Diversion Irrigation Area

2.1 Lack of Scientific Data Support and Intelligent Decision-Making System

In the current practice, the water resources management in the Yellow River irrigation area still relies on experience judgment and manual operation to a large extent, which is obviously unable to meet the needs of modern water resources management[7]. The lack of scientific data support makes it difficult for managers to accurately grasp the real-time status, changing trends and potential risks of water resources[8]. Traditional data collection methods often have problems such as incomplete, inaccurate and untimely data, resulting in managers unable to obtain comprehensive and accurate water resources information, so that it is difficult to make scientific and reasonable decisions[9]. In addition, the lack and imperfection of data also make it difficult to predict and warn water resources, and it is impossible to find and deal with potential water resources risks in time[10].

2.2 Difficulties in Collecting Water Charges and Poor Management

The effective implementation of water charges is crucial for the equity and sustainability of water resource management. However, the Yellow River irrigation area faces significant challenges in water charge collection, with issues of poor management becoming increasingly apparent. Currently, the water resources management system in the Yellow River diversion irrigation area is not fully organized, resulting in overlapping management structures and unclear rights and responsibilities. This confusion leads to inconsistent water charge collection standards and hampers effective collection efforts. Additionally, inadequate metering facilities hinder accurate charge collection; the lack of advanced measuring equipment often results in measurement errors. Mismanagement further complicates the situation. In certain areas, lax oversight allows for the misappropriation and abuse of water charges, undermining fairness and effectiveness in collection and disrupting the proper management of water resources. Furthermore, low transparency and a lack of openness in the water charge collection process diminish public trust, exacerbating the difficulties in collection efforts.

3 Application Advantages of Digital Twin Technology in Water Resources Management of Yellow River Diversion Irrigation Area

3.1 Accurate Simulation and Prediction

Digital twin technology, as a cutting-edge information tool, has demonstrated significant benefits in accurately simulating and predicting water resources management in the Yellow River irrigation area[11]. This technology leverages real-time data synchronization and updates to ensure that the virtual model remains closely aligned with the actual conditions of the irrigation area. Its real-time capabilities encompass various aspects, including changes in water resources, water quality fluctuations, and hydrological responses. By accurately simulating these multidimensional data, digital twin technology uncovers the underlying patterns of water distribution, flow, and transformation, providing a scientific foundation for the efficient management and scheduling of water resources[12][13][14][15].

Digital twin technology can simulate hydrological processes under different natural conditions such as rainfall and evaporation to predict water quantity change and water quality in irrigation areas, and provide decision support for rational allocation and utilization of water resources [16]. At the same time, through the simulation of the running state of the water conservancy facilities in the irrigation area, the operation efficiency and maintenance needs can be predicted, which provides a basis for the optimal design and operation management of the facilities [17].

3.2 Efficient Data Analysis

Efficient data analysis is one of the important applications of digital twin technology in water resources management in Yellow River irrigation area. The built-in intelligent algorithm module of the technology has powerful data processing and analysis capabilities, which can carry out multi-angle and deep-level intelligent analysis of the operational data of the irrigation district, so as to provide strong support for the decision-making department and realize the high efficiency and precision of water resources management[18].

Digital twin technology collects and processes the real-time operation data of irrigation areas, such as rainfall, evaporation, water level, flow, etc., and uses intelligent algorithms to deeply analyze and mine these data. These algorithm modules include machine learning, data mining, pattern recognition and other methods, which can reveal the inherent laws and trends of data from different angles, and find potential problems and opportunities[19]. Through the analysis of the data, the digital twin technology can generate early warning tips to help managers find possible risks such as water shortage and pollution in the irrigation area in time, and take corresponding measures to prevent and cope with them[20].

3.3 Intelligent Decision Support

Intelligent decision support is the key for digital twin technology to play a core role in water resources management in Yellow River irrigation district. By integrating advanced data collection, processing and analysis functions, the technology realizes comprehensive and accurate grasp of irrigation district water situation data, and provides scientific and efficient decision support for managers.

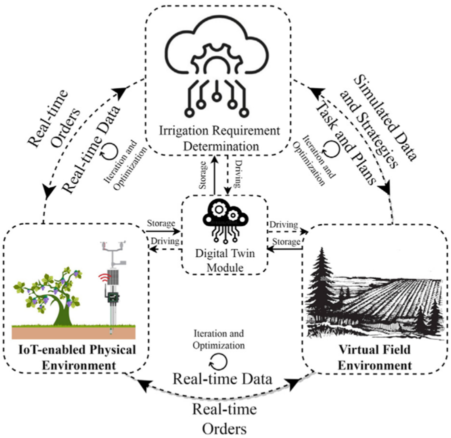

Fig. 2. The proposed irrigation determination framework

Digital twin technology, by deploying a network of sensors, collects real-time water volume data from the irrigation area. This data, after preprocessing and analysis, can accurately reflect the status and trends of water resources in the irrigation area[21]. Moreover, digital twin technology also has the capability for precise measurement of water usage, accurately recording the water consumption and timing for each water bucket, providing data support for the rational allocation of water resources. Additionally, digital twin technology can remotely and automatically control sluice gates (valves). Through remote control systems, managers can adjust the gate openings in real-time, thereby achieving precise control over water flow. This automated control not only enhances management efficiency but also reduces errors and costs associated with manual operations. Based on real-time data, digital twin technology offers intelligent decision support for managers. The technology, equipped with built-in intelligent algorithm modules, can conduct in-depth analysis of the collected data, predict future water demand and hydrological changes, and provide robust support for managers to develop scientific irrigation strategies and optimize water resource allocation[22]. Figure 2 illustrates the schematic diagram of the irrigation principle.

4 Construction Path of Digital Twin Technology in Yellow River Diversion Irrigation District

4.1 Requirements Analysis and Planning

Requirement analysis serves as the foundation for constructing a digital twin system. By conducting a thorough analysis of the Yellow River diversion irrigation area, we can gain insights into its topography, water resource distribution, water management facilities, and operational modes. Engaging with irrigation district management and stakeholders is also essential to understand their needs and expectations, which will help clarify the specific applications of digital twin technology in irrigation management. To ensure successful implementation, it is vital to establish clear requirements, detailed planning, and implementation strategies. The planning phase should involve a comprehensive assessment of the irrigation area's conditions and the technology's feasibility. Clearly defined objectives, functional orientations, and technical approaches for the digital twin system must be outlined. Additionally, a well-structured timetable and resource allocation plan should be developed to facilitate smooth project execution. Throughout the planning and implementation process, a focus on the relevance and effectiveness of the technology application is crucial[23]. This entails selecting appropriate digital twin technologies and methods based on the specific challenges and needs of the irrigation area. Effectiveness requires monitoring the practical outcomes during implementation to ensure that the technology addresses issues and enhances management efficiency. Therefore, establishing a scientific evaluation mechanism is necessary to regularly assess the digital twin system's application, identify problems promptly, and make necessary adjustments and optimizations.

4.2 Strengthen Data Integration and Management

Establishing a unified data integration platform is the basis of data integration and management. The platform needs to have powerful data processing and storage capabilities, which can support real-time collection, transmission, storage and analysis of massive data. At the same time, the platform should also provide a friendly user interface and convenient operation tools to facilitate users to conduct data query, analysis and visual display. The core task of data integration platform is to integrate and manage all kinds of data resources in irrigation area. These resources include water resources monitoring data, meteorological monitoring data, farmland monitoring data and equipment monitoring data. By integrating these data, we can fully understand the operation status of irrigation area and provide data basis for decision support.

To achieve interoperability among heterogeneous data sources, we have implemented custom interfaces to connect with existing monitoring systems. This approach not only circumvents issues related to data format conversion and analysis but also ensures the timeliness and accuracy of the data. Through interface integration, we have facilitated data sharing and collaborative efforts across different systems, thereby enhancing data utilization efficiency. Moreover, the establishment of an irrigation district knowledge base is one of the key objectives in the integration and management of irrigation district data. Serv-ing as an aggregation and abstraction of irrigation district data, the knowledge base enables in-depth understanding and mining of the data's value. The schematic of the Intelligent Irrigation District Integrated Management Platform, as shown in Figure 3, provides managers with an intuitive decision-support tool.

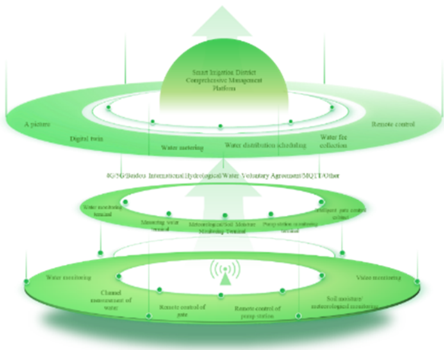

Fig. 3. Smart Irrigation District Comprehensive Management Platform

4.3 Building a Digital Twin

On the basis of establishing a unified knowledge base, we build a multi-dimensional digital twin model including water resources, farmland and facilities and equipment by integrating multi-source data, and realize the comprehensive mapping and "cloning" of the irrigation district system. This model not only enhances our understanding of irrigation system, but also provides strong support for decision-making. Figure 4 shows a schematic diagram of the construction of the digital twin[24] [25].

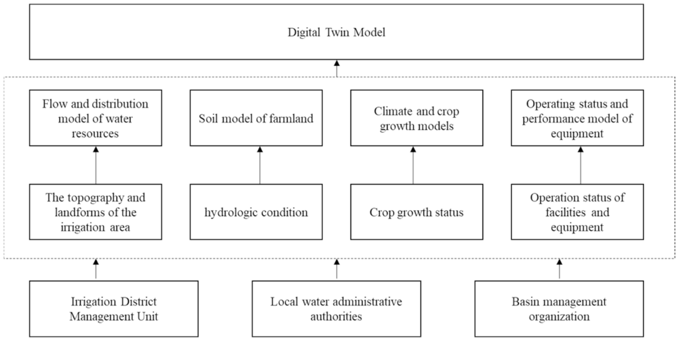

Fig. 4. Schematic diagram of digital twin model construction

Digital twins are powerful because they can be updated in real time. By connecting to field monitoring systems, these models continuously receive the latest data, allowing them to adjust automatically and remain consistent with actual conditions. This capability provides timely and accurate information for decision-making. Through the analysis and simulation of the digital twin model, we can gain insights into the operational rules and challenges within the irrigation district, laying a scientific foundation for optimal scheduling and decision-making. Additionally, the model can forecast future trends and potential issues, supporting proactive countermeasure development. In the water resources allocation module, the key decision variable is the allocation of water among different departments. The objective is to maximize water allocation benefits while ensuring fairness across regions, subject to constraints such as total water quantity and minimum consumption. Specifically, the water supply benefit is defined as the sum of the water distributed by various departments, multiplied by the value generated per unit of water.

$$\max B = \sum\nolimits_{i=1}^{m} * \sum\nolimits_{j=1}^{n} * p_{ij} * W_{ij},$$

Where: B is the income of water supply in the irrigation area (yuan); pij is the value of unit water quantity produced by different water consumption departments in different regions (yuan /m^3); Wij allocates water to different water sectors in different regions (m^3). Objective function 2: equality of water distribution in different regions and different water departments of irrigation district. Fairness is expressed by the standard deviation of the ratio of actual water distribution to water demand.

$$\min f = \sqrt{\frac{\sum_{i=1}^{m} \sum_{j=1}^{n} \left(\omega_{ij} - \bar{\omega_{ij}}\right)^2}{m \cdot n}}, \omega_{ij} = \frac{W_{ij}}{W_{xij}}$$

Where: f is the standard deviation of the ratio of actual water distribution to water demand; ωij is the ratio of actual water distribution and water demand of different water departments in different regions; Wxij 'is the net water demand of different water sectors in different regions (m 3).

Constraints: (1) Constraints on available water supply, the total water distribution to meet the requirements of available water supply. Σ Wij⩽Wg n j=1 m i=1, (4), where: Wg is the available water supply of this water distribution in the irrigation area (m 3). (2) Minimum water consumption constraints, different regions of different water departments of the distribution of water should not be less than the minimum water consumption. Wij⩾minWij,

4.4 Accelerate the Construction of Automatic Control of Water Conservancy Facilities

Intelligent transformation is a key step in the automatic control of water facilities, involving the technological upgrading of key facilities such as gates and pumping stations, as well as the introduction of advanced sensors, actuators and control systems. Through the installation and configuration of these intelligent devices, we can achieve real-time monitoring and accurate control of the operating status of water facilities. Remote automation control is the core of intelligent transformation, through the establishment of a stable and reliable communication network, the water conservancy facilities and the central control system are connected to achieve real-time data transmission and remote command execution. The automatic control system can automatically adjust the operation of water conservancy facilities according to real-time monitoring data and preset algorithms to ensure accurate control. In addition, the rapid response capability of the automatic control system enables it to respond quickly to emergencies and reduce the waste and loss of water resources. Using digital twins, we assessed the potential ecological impacts of different water management strategies and found that adopting optimal water allocation schemes could mitigate impacts on downstream ecosystems and protect biodiversity. Table 1 shows the efficiency comparison and improvement before and after the implementation of the rule.

Table 1. Schematic diagram of digital twin model construction

norm	before carry out	after carry out	improvement rate
water use efficiency	75%	95%	20%
accuracy of water billing	70%	100%	30%
management costs	100%	75%	25%
predictive accuracy	70%	85%	21.4%

5 Conclusion

In this study, digital twin technology is successfully applied to the water resource management in the Yellow River Irrigation District (YRID) to achieve real-time monitoring, accurate analysis and optimal scheduling of water resources by constructing an accurate virtual model. The application of this technology significantly improves the utilization efficiency of water resources, reduces waste, and optimizes the water fee collection and management process. In the future, the digital twin technology is expected to be promoted in a wider range of water management practices, especially in the study of climate change adaptation and the impact of extreme weather events on water resources. In addition, by integrating advanced technologies such as Augmented Reality (AR), Virtual Reality (VR), Artificial Intelligence (AI), and Machine Learning, the digital twin model will provide a more intuitive and interactive user experience, as well as higher prediction accuracy and adaptive capabilities. Facing the challenges of data security and privacy, there is a need to develop more advanced data encryption and access control technologies, as well as to improve users' understanding of and trust in the technology through training and education. The application of digital twin technology will help to realize sustainable management of water resources, support the clean water and sanitation goals of the United Nations Sustainable Development Goals, and reduce negative impacts on the ecosystem, providing additional solutions for global water management.

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