

Overview of the Research Status of Intelligent Water Conservancy Technology System

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Abstract: A digital twin is a new trend in the development of the current smart water conservancy industry. The main research content of intelligent water conservancy is clarified. This paper first summarizes and combs the relevant system architecture of smart water conservancy, and puts forward a smart water conservancy framework based on digital twins, highlighting the characteristics of virtual and real interaction, and symbiosis of the water conservancy twin platform. Secondly, the status quo of intelligent water conservancy “sky, air, ground and water” integrated monitoring technology, big data and artificial intelligence, model platform technology, knowledge graph and security technology is analyzed. From the perspective of application, the research progress of each technology in water security, water resources and hydraulic engineering is reviewed. Although the construction of smart water conservancy has made remarkable progress, it still faces many challenges such as data governance, technology integration and innovation, and standardization. In view of these challenges, this paper puts forward a series of countermeasures, and looks forward to the future development direction of intelligent water conservancy.



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Keywords: digital twin; intelligent water conservancy; virtual–real interaction; standardization; development direction

1. Introduction

With the rapid development of climate change, the economy and society, global extreme hydrological events continue to intensify, and the contradiction between supply and demand of water resources becomes increasingly prominent, and has become the focus of human attention [1]. For example, the European Commission’s multi-stakeholder Water Europe platform calls for a move towards a water-smart society [2,3]. This urgently needs a new generation of information technology and traditional water conservancy industry combination. Relying on cutting-edge technologies such as the Internet of Things (IoT), big data and artificial intelligence (AI), intelligent water conservancy systems can not only promote high-quality development of water conservancy, and strengthen watershed governance and management, but also effectively address the challenges of climate change [4,5]. Therefore, intelligent water conservancy has gradually become an important means of digital water control. As of 3 June 2024, Web of Science retrieved a total of 1487 journal articles on the topic of “smart water conservancy”, of which 1172 papers were published in the last five years, showing the increasing research heat in this field. In the context of the rapid development of smart water conservancy, the digital twin, as an emerging technology, came into being, bringing new opportunities for the development of new quality productivity

of water conservancy and the improvement of the high-quality management mode of the water conservancy industry [6]. A digital twin is a virtual representation of a physical object or process capable of gathering information from the real environment to demonstrate, verify, and simulate the current and future behavior of a physical entity [7]. Digital twin water conservancy is the application of digital twin theory in the water conservancy industry, which realizes intelligent decision-making and system optimization through real-time data monitoring, simulation analysis and optimization decision-making, and promotes the understanding and management of complex water conservancy systems [8,9]. In recent years, China's Ministry of Water Resources has attached great importance to the development of smart water conservancy and digital twin technology. Key initiatives include the master plan for the construction of smart water conservancy, the formal proposal of the "digital twin watershed" and the organization of a conference on digital twin watershed construction. Additionally, a series of water conservancy digital twins has been proposed, along with the promulgation of key points for water conservancy project construction. Finally, guiding opinions have been issued to promote the digital twin construction in water conservancy projects. Figure 1 shows the progress of the smart water digital twin.

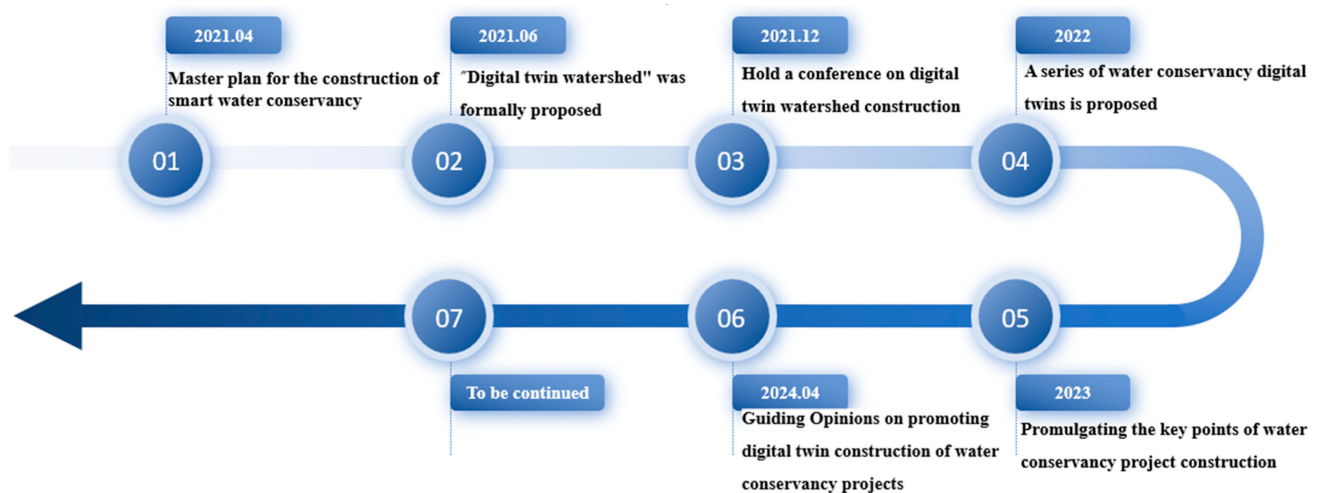


Figure 1. Progress of smart water conservancy digital twin.

At present, smart water conservancy has been rapidly developed and widely used in water security, water resources management, water conservancy engineering and other aspects, and the intelligent level of watershed management and governance has been significantly improved. However, smart water conservancy still faces many deficiencies in the development process, and there is still a certain lack in the full application of the new generation of information technology in digital twin water conservancy [8,10]. It is mainly reflected in the following aspects. First, there is a lack of comprehensive monitoring and perception ability. At present, the intelligent monitoring level of all kinds of water conservancy facilities is low. For example, the interconnected sensing system of water conservancy and hydropower projects faces many challenges in the aspects of multi-observation data fusion, protocol interconnection and interactivity, and it is difficult to meet the needs of high intelligence, high precision and high time air-to-ground observation [11,12]. Improving comprehensive monitoring techniques is therefore essential. This study will focus on the research status of constructing the integrated sensor network of sky, air, ground and water, in order to realize the three-dimensional and intelligent water-sensing system. Second, the 3D simulation ability of the water conservancy scene is insufficient. First of all, the capability of multivariate data fusion and iterative update is insufficient, and the real-time feedback mechanism is lagging, which affects the real-time analysis and decision-making of the water conservancy business. Secondly, the computing power of the simulation platform cannot support high-frequency and high-precision dynamic simulations, resulting in insufficient fidelity

of the 3D digital twin scene. Finally, the integration of spatial analysis and professional modeling modules involved in the water conservancy business is not deep enough, and it is urgent to improve the level of simulation and intelligent application [13]. Therefore, this paper deeply analyzes the establishment of a high-precision multi-fusion data substrate, the construction of digital twin scenarios integrated by BIM and GIS, and the application examples of digital twin water model platform technology, hoping to provide valuable experience for subsequent researchers. Third, the function of intelligent decision analysis is still insufficient. The traditional water conservancy model has some problems, such as poor real-time performance, poor prediction effect and a low data utilization rate. Therefore, there is an urgent need to combine emerging technologies such as big data, machine learning and knowledge graphs to improve decision-making ability [14]. Among them, big data technology can improve the representation and value of data by integrating a large number of real-time data from different sources, so as to make decisions more accurate. At the same time, artificial intelligence, especially machine learning, can perform intelligent analysis and prediction of hydrological data, such as flood forecasting. The construction of a water conservancy knowledge map can integrate the database of a forecast scheduling scheme and the database of business rules to provide deep support for the decision-making process. In addition, this paper summarizes the cloud network convergence architecture based on digital twins, which provides efficient data updating and real-time synchronization capabilities for water resources management by migrating resource-intensive tasks to edge and end devices. At the same time, the combination of blockchain technology and smart sensors ensures the high reliability and authenticity of the data, thus improving the security of the water conservancy digital twin data chain.

This study aims to focus on the research status of key technologies and applications of smart water conservancy, and integrate the digital twin into a smart water conservancy system as an important technology to provide a new perspective for the development of smart water conservancy, with a view to providing useful references for the application of digital twin technology in water resources management. In order to achieve this goal, this study uses the keywords “digital twin”, “intelligent water conservancy” and “water resources management” in academic databases such as Web of Science and CNKI to collect and classify relevant literature. The structure of the paper is as follows. Firstly, the introduction will introduce the background of intelligent water conservancy, research status and the contribution of this paper. Secondly, based on the existing literature, a smart water conservancy framework based on the digital twin is proposed. Then, the application status of an intelligent water conservancy system in water security, water resources management and water conservancy engineering is discussed. Then, the challenges faced by smart water conservancy and corresponding solutions are analyzed, focusing on data problems, technology integration, professional personnel training and standardization of smart water conservancy construction. Finally, we summarize the research content and look forward to the future research direction.

2. Smart Water Conservancy System Based on Digital Twin

The overall architecture of intelligent water conservancy based on digital twins should be able to describe the whole process of perception data from collection, transmission, analysis and processing, to embodiments of symbiosis, common intelligence and real-time interaction. Using the application of the new generation of information technology (such as big data, artificial intelligence, Internet of Things, cloud computing, mobile Internet, etc.), establish the digital twin data and model integration method, study its operation mechanism, build the smart water conservancy twin, and design the smart water conservancy platform driven by the digital twin. Real-time monitoring, diagnosis, analysis, decision and prediction of water management are realized, providing new ideas for intelligent operation, accurate control, and safe operation and maintenance [15].

On the basis of this structure, according to the specific research object or application level, many intelligent water conservancy-related system architectures are derived, such as

the digital twin water conservancy engineering system [16], etc. The specific contents of each system architecture are summarized in Table 1.

Table 1. Summary of related system architecture of smart water conservancy.

System Name	System Content
Digital twin hydraulic engineering system [16]	Physical layer, data layer, service logic layer, user interaction layer
Application research of the “Four Pre-stages” intelligent water conservancy platform for flood control based on digital twin [17]	Data baseboard construction, perception system construction, digital twin model construction, intelligent decision and optimization
Digital twin river basin flood control application technology framework [18]	Resource layer, data layer, twin layer, application layer
Research on standard specification system of digital twin watershed [19]	Basic commonality, information infrastructure, digital twin platform, business application, security, construction, operation and maintenance
Digital twin basin architecture [20]	ABCDMEETS (Artificial intelligence, big data, cloud computing, digital twin, Digital Mainline, model systems engineering, air–Earth integrated network, edge computing, Internet of Things, simulation) digital twin basin architecture
Intelligent water conservancy Integrated Management Platform [21]	Physical layer, blockchain layer, interface layer, application layer, regulatory layer
Architecture of water conservancy modernization [22]	Big perception stereo system, big network interconnection system, big data cloud center system, brain fusion system, big application system
Smart water system framework [23]	Perception layer, network layer, knowledge layer, application layer
Theoretical framework of intelligent water network [24]	Construction and key technologies of water physical network, water information network and water management network
Real-time runoff prediction system based on digital twin [25]	Physical layer, perception layer, transmission layer, digital layer, decision layer

According to the summary of the relevant system architecture of smart water conservancy in Table 1, the current smart water conservancy system usually adopts a multi-level structure design, such as the perception layer, the network layer, the knowledge layer and the application layer. This design clarifies the function of each component, making it easy to manage and maintain. In addition, the overall framework of digital twin water conservancy project construction [26] and the framework of digital twin basin construction [27] both reflect similar characteristics, that is, the digital twin platform is adopted as the core component. The platform is composed of the data base, model base and knowledge base. Based on the above comprehensive research of intelligent water conservancy and the digital twin framework, this paper aims to propose a digital twin intelligent water conservancy framework with virtual–real interaction and symbiosis characteristics. This framework will integrate the advantages of the multi-tiered structure and the digital twin platform to further enhance the management efficiency and service capacity of the smart water system. The framework is divided into perception layer, network layer, platform layer and application layer from bottom to top, and a network security system is set up vertically. As shown in Figure 2, the perception layer mainly employs satellites, drones, sensors, unmanned vessels and other technologies for multi-dimensional sensing of water conservancy information. It also enables interaction with infrastructure through the Internet of Things. The network layer mainly consists of three parts: communication facilities, information networks and cloud–network integration. Communication facilities include NB-IoT, 5G and Zigbee. Information networks comprise the Wide area network, Metropolitan area network and Department network. Cloud–network integration includes the Water cloud, Public cloud and Private cloud. The platform layer includes the data backplane, model platform and knowledge platform, facilitating virtual interaction among physical entities, creating a symbiotic and intelligent effect. The data backplane includes data mapping, data

collection, data processing and data service. The model platform consists of the Hydraulic professional model, Mechanism analysis model, Mathematical–statistical model, Hybrid model and Intelligent algorithm library. The knowledge platform encompasses business planning, expert experience, forecast scheduling and the historical scene. The application layer includes basin flood control, water resources management and allocation, and N services. This optimized content provides a structured overview of the intelligent water conservancy framework, emphasizing the integration of various levels and components to achieve efficient and intelligent water management practices.

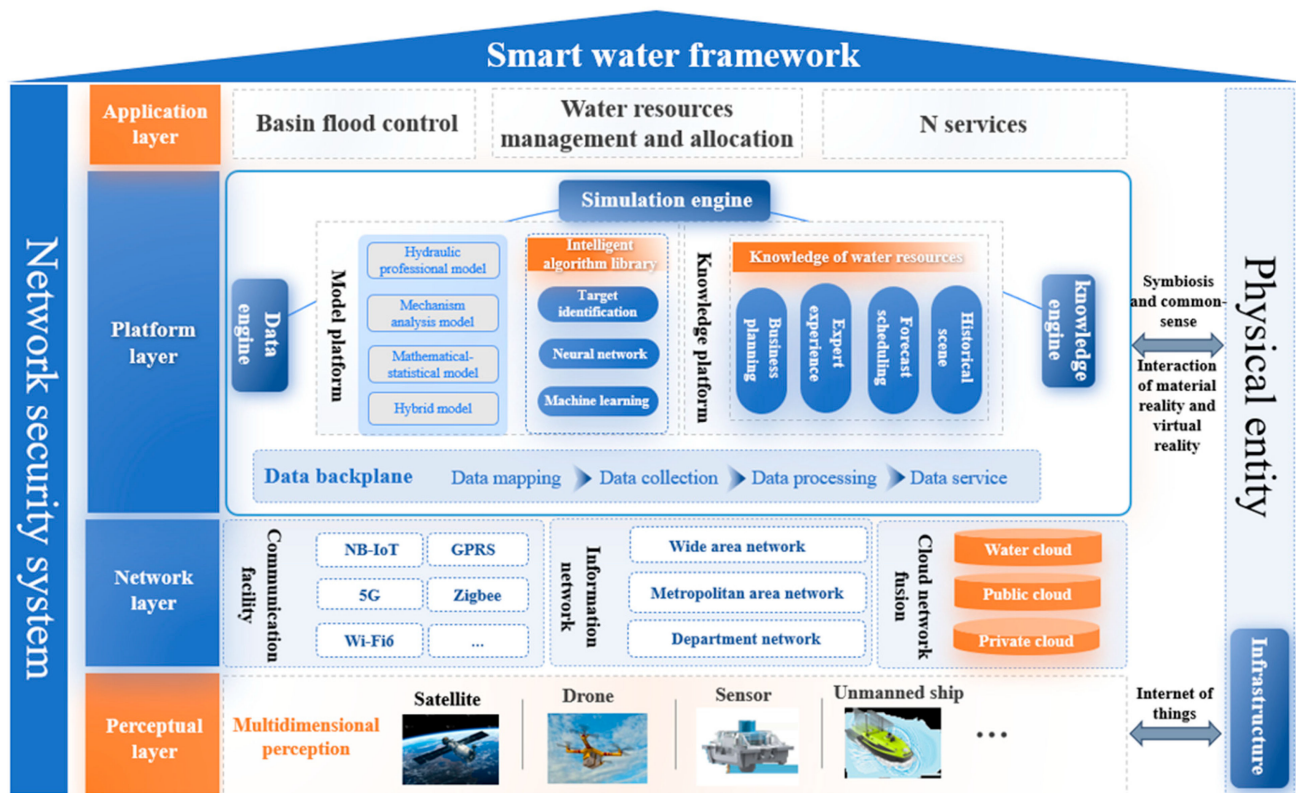


Figure 2. Overall framework of intelligent water conservancy.

3. Status Quo of Key Technologies of Smart Water Conservancy

3.1. “Sky, Air, Land and Water” Integrated Monitoring Technology

The multi-dimensional perception of water conservancy is the basis of realizing the water conservancy digital twin. The construction of an integrated sky, air, earth and water sensor network is expected to solve the problems of integrated spatial information facility construction, multi-observation fusion, protocol interconnection, subject interaction and high perception [28]. Multi-dimensional monitoring technology integrates remote sensing, UAV and sensor technologies to build an integrated monitoring system to collect multi-dimensional data such as the water conservancy system, water resources and environmental parameters in real time [29].

In space-based monitoring, satellite remote sensing is used as the main monitoring means, such as Fengyun series meteorological satellites and SWOT satellites [30]. Using these satellite data, dynamic monitoring [31] and evolution analysis [32] of water resources can be realized. However, the resolution of some remote sensing data is insufficient to meet the needs of refined water management, especially for small-range and fine-grained monitoring and analysis. In space-based monitoring, UAV technology has the characteristics of current situation, high precision and high efficiency. At present, combined with deep learning image technology, drones can identify and locate specific targets, improving dynamic perception. Ground-based monitoring mainly uses wireless sensor networks to flexibly

deploy and transmit data through wireless networks (such as Wi-Fi, Bluetooth, Zigbee, etc.) to adapt to the complexity of water system monitoring requirements. For example, multiple sensors are used for periodic synchronous data acquisition, and, combined with interpolation and grid mapping technology, a data twin system is established to realize real-time water conservancy monitoring [33]. However, wireless sensor networks are subject to energy limitations and have limited service life and performance. Energy-saving clustering protocols and lightweight machine learning technologies can be integrated to improve the effectiveness and accuracy of sensor networks [34]. At the same time, the concept of the virtual sensor service network and multi-platform and multi-sensor flexible observation service method are proposed to address the difficulties of task-driven bidirectional feedback control of sensor networks, so as to realize unified planning and real-time sharing of service [35]. At present, the construction of digital twin basins requires comprehensive basin operation status and accurate digital representation. Therefore, the primary key to creating digital twin basins is to take the water environment array sensor technology of key basins as the data source and multi-source data fusion as the technical means [36]. In water-based monitoring, unmanned survey ships equipped with multi-beam sounding systems are generally used to collect underwater data [37].

Finally, IoT technology is deployed through sensors at key points in the physical entity, transmitting the necessary information to the digital twin for data interaction. In the intelligent water conservancy basin scheduling, Internet of Things technology has changed the problems of incomplete monitoring information, low transmission efficiency and insufficient computing speed, which has brought major breakthroughs for basin scheduling. A watershed intelligent scheduling technology system based on Internet of Things technology has been proposed [5]. In the next step, a new water conservancy perception system based on intelligent Internet of Things terminals should be strengthened to achieve convenient, thorough and intelligent water conservancy perception, and provide more comprehensive data support for digital twins [38].

3.2. Big Data and Artificial Intelligence Technology

Big data and artificial intelligence are the main technical support for digital twins to realize the functions of cognition, diagnosis, prediction and decision making [39]. Big data has “5V” characteristics, that is, Volume, Velocity, Variety, Value and Veracity [40]. The integration of different data, the iteration of native data and lifetime data, will produce greater data representation and higher data value. Artificial intelligence and big data are interrelated fields. AI requires large amounts of data for training and optimization, while big data requires AI algorithms and techniques to process and analyze the data. In the field of water, machine learning has been continuously developed and applied. It leverages big data, advanced algorithms and sensor technology to enable intelligent analytics and predictions.

Studies have shown that machine learning can monitor water quality in real time [41], predict change trends [42], improve the efficiency of water conservancy systems, and improve flood vulnerability assessment [43], for example, water quality elasticity prediction using multiple algorithms [44], or flood prediction through support vector machines [45]. In addition, the improved neural network structure also improves the accuracy of water quality prediction [46]. Through AI, the water sector can better process large-scale data, uncover hidden patterns and trends, and support data-driven decisions. In the water conservancy digital twin system, the digital twin senses the real-time data from the physical entity and is trained by various artificial intelligence algorithms to complete the tasks of diagnosis, prediction and decision making. Taking the digital twin-enabled water plant as an example, the key parameters of different sections of the water plant are monitored by a digital twin engine, and the parameters of the process equipment are optimized in real time by combining intelligent models.

3.3. Cloud Network Convergence Architecture Based on Digital Twin

The cloud network convergence architecture is the virtualization and integration technology framework of the network and cloud computing basic resource layer, which is regarded as the key link between the network, cloud services and computing power infrastructure, laying the foundation for the new information infrastructure. The cloud network fusion architecture ensures the timeliness of data update and synchronization with the physical basin [47]. The advantage of the cloud network integration technology of digital twins is that it considers the integration of cloud, edge and end, migrates resource-intensive tasks to the edge and end of IoT devices, and relies on the cloud native platform to realize resource sharing and network resource management and scheduling. The infrastructure needs to meet the requirements of high bandwidth, low latency and accurate simulation to support the efficient operation of digital twins [48]. The cloud computing platform can integrate network information perception, communication and intelligent computing functions to improve network intelligence, and operation and maintenance [49]. Cloud computing promotes the evolution of digital twin services into a cloud model to achieve high-precision simulation computing requirements and improve resource utilization [50]. Figure 3 shows the triangular model of the water conservancy twin “cloud–edge–end”.

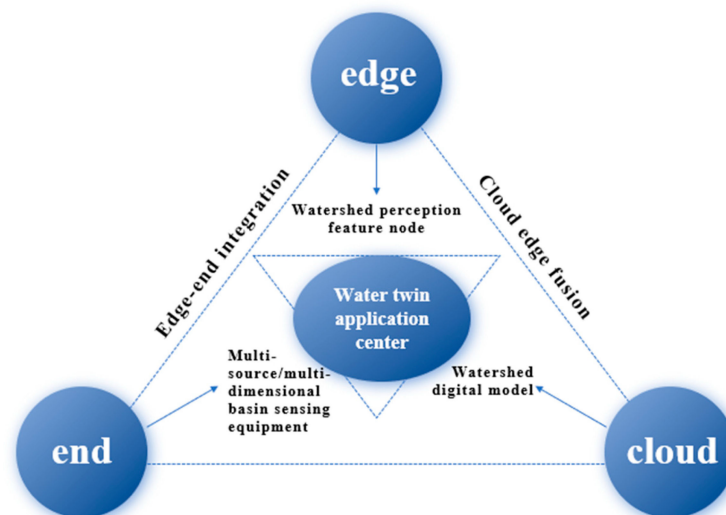


Figure 3. Triangle model of water conservancy twin “cloud–edge–end”.

The cloud network convergence technology system based on digital twins mainly includes three key technologies: (1) river basin ubiquitous connection and collaboration technology, which realizes network ubiquitous connection and collaboration by integrating computing power nodes through hierarchical connection architecture [51]; (2) cloud access and inter-cloud interconnection technology, using SD-WAN and SRv6 technologies to achieve network expansion and collaboration, ensuring performance and reliability [52,53]; and (3) cloud network resource supply and differentiated service technology to provide resource pool and differentiated bearer services to ensure the differentiated service capability of the network [54]. At present, the research on cloud network integration in the field of water conservancy informatization is in the application and exploration stage, and it is necessary to deepen the research on cloud native technology in the cloud network integration scenario, so as to improve the capability of the digital twin basin information infrastructure [55].

3.4. Digital Twin Platform Technology

This section introduces the research related to digital twin model construction and visualization, respectively, focusing on the construction of data substrate, digital twin scene

construction based on the fusion of BIM and GIS, and digital twin water conservancy model platform technology.

3.4.1. Data Backplane Construction

At present, problems such as classification inconsistency and format incompatibility exist in the construction of data baseboards, leading to poor generality and data fusion challenges [56]. Therefore, the establishment of high-precision multi-fusion data baseboards has become a key issue at present. One study [57] integrates tilt photogrammetry, airborne LiDAR, multi-beam sounding and other means. The three-dimensional model of an integrated watercourse is successfully constructed. An airborne LiDAR point cloud is used to improve the accuracy of the oblique photography model, and a multi-beam system is used to display underwater scenes in detail. In addition, another study [58] uses three-dimensional mapping technology to simulate the construction of digital twin baseboards, realize elastic update of scenes, and establish an early warning mechanism through satellite and UAV remote sensing, which innovatively solves the shortcomings of multi-source data generation, update and management, and provides key technical support for intelligent water conservancy.

3.4.2. Construction of Digital Twin Scenarios Integrating BIM and GIS

The integration of BIM and GIS plays a key role in digital twin water conservancy, achieving data integration through standardized data interfaces and metadata management, and successfully achieving integration between models through spatial reference frame alignment to support multi-level data presentation and interaction. The research shows that [59] the multi-dimensional water conservancy digital twin scene is constructed by integrating BIM and the oblique photography model into the 3D GIS platform, which provides data support for the water conservancy GIS + BIM scene. The BIM model is transformed for GIS scenarios, and GIS and BIM data are integrated to generate paging scheduling logic of LOD (Level of Detail) models at all levels, realize lightweight integration of water GIS + BIM scenarios, and provide data support for digital twin platforms [13].

3.4.3. Digital Twin Water Model Platform Technology

Digital twin water model platform technology has many applications and advantages. The core of the hydraulic digital twin platform is to build professional models including hydrology, hydraulics, sediment dynamics, water resources, water environment, soil and water conservation, and water engineering safety, as well as intelligent models such as remote sensing, video and natural language processing, and combine visual models to form a comprehensive simulation platform. This comprehensive model combination can provide detailed, quantitative, dynamic and intuitive computational analysis support for smart water conservancy, help find problems, propose solutions and optimize scheduling schemes, and realize dynamic interaction and coupling simulation of prediction and scheduling [60].

The visual model is an important model support for 3D simulation, providing real-time rendering and visual presentation for simulation. The visualization models required for 3D simulation of water conservancy should include the visual rendering model of the natural background surrounding water conservancy projects (such as daytime and night in different seasons, wind and snow fog of different magnitude, sunshine variation, light and shadow, water body, etc.), the dynamic visualization mimic simulation model of the reservoir flow field, the monitoring and safe operation model of water conservancy project, and the deformation model of typical geological disasters in a reservoir area, etc. Based on real data, it can realize real visual simulation of the water conservancy hub and reservoir area [13].

With the continuous improvement of business functions, the application of digital twin technology in the field of water conservancy is also deepening. Through rehearsal and simulation, this technology has realized the exploration of planning, design and future prediction scenarios in the field of digital twin watershed and hydraulic engineering, and

realized the dynamic interaction and coupling simulation of forecast and scheduling [61]. Related studies also put forward the design and combination of agents to optimize the service combination scheme to meet the demand [62]. In addition, the development of 3D visual simulation systems combines high-precision DEM data and the hydrodynamics model to realize a large range of water surface dynamic simulations, and provides a real-time and efficient visual simulation method for watershed flow speech [15].

In order to standardize the application of a mathematical model in the water conservancy industry, an open idea is put forward, a model base is built and a standard evaluation process is introduced to make the model a recognized component in the industry. In addition, the platform supports the development of pre- and post-processing tools to provide convenient numerical simulation services, and improve computing efficiency and concurrency. With the continuous improvement of business functions, big data analysis, and comparison and in-depth mining research will be carried out to provide support for engineering design, flood control scheduling and disaster warning [63].

In order to overcome the limitations of the traditional digital watershed platform, the Web-based digital twin model realizes the virtual simulation of geographical elements through the browser, displays the watershed water environment and provides decision support. Multiple 3D modeling methods and spatio-temporal modeling of multi-source data provide support for accurate watershed management [64]. The technical solutions proposed in the literature, such as fine-grained decomposition, nested reuse, assembly orchestration methods, and microservices-based packaging and publishing technologies, provide valuable experience and feasible solutions for the construction, application and lifecycle management of the model base of the hydraulic digital twin platform [65].

3.5. Knowledge Graph

The knowledge graph concept is a semantic network in which nodes represent entities or concepts, and edges represent semantic relationships between them [66]. Structured knowledge is extracted from massive heterogeneous data and combined with downstream applications in various industries [67]. In the construction of intelligent water conservancy, the knowledge graph is widely used in spatial query services, and intelligent question and answer [68–71], as well as in water conservancy business applications such as historical scene replay of water conservancy objects [72]. The construction tasks of water conservancy knowledge include the forecast and dispatching scheme database, knowledge graph database, business rule database, historical scene pattern database and expert experience database. The hydraulic knowledge engine is used for knowledge representation, extraction, fusion, inference and storage [73]. The key technologies of knowledge graph construction include data acquisition, knowledge extraction and knowledge fusion to realize the deep ordering from knowledge processing and knowledge graph construction to knowledge expression [74]. Figure 4 shows the basic construction process of the knowledge graph.

The research shows that the hydraulic knowledge query and recommendation method based on digital twins adopts the KR-EAR model, collects the hydraulic knowledge map of the digital twin watershed, uses K-means clustering to represent the hydraulic information resources in vector, and forms the candidate resource set. It solves the problems of insufficient resource acquisition and the inaccurate recommendation effect in the water conservancy information inquiry and recommendation in the past [75]. In the process of constructing the water conservancy knowledge map based on the knowledge annotation platform, 43 kinds of water conservancy entities and 110 kinds of entity relationships are covered, which significantly improves the coverage and accuracy of knowledge [76]. However, the existing water knowledge map still has the problems of small scope of knowledge coverage and no close connection with actual business, so the Water Knowledge map for digital twin project (KG4DT) [77] came into being.

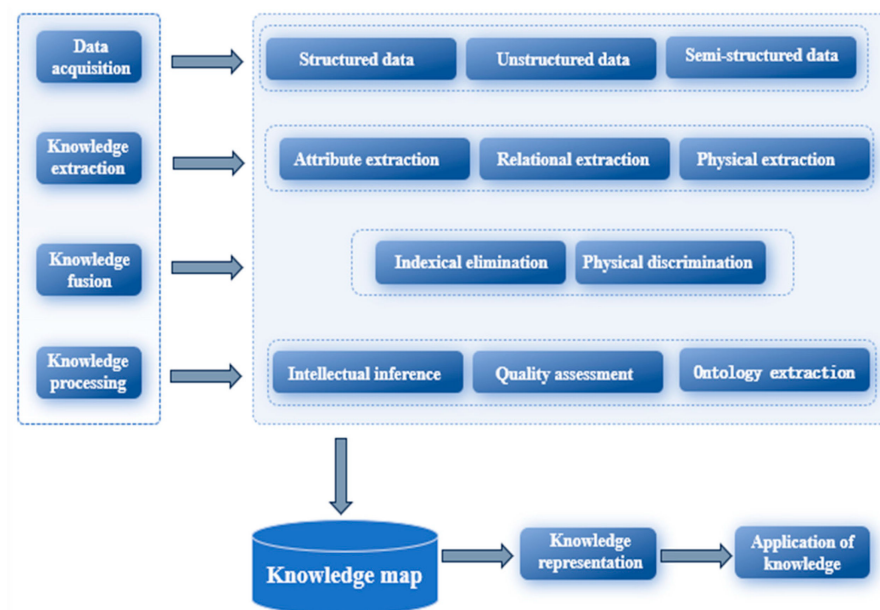


Figure 4. Basic construction process of knowledge graph.

3.6. Security Technology Based on Blockchain

At present, the challenges of data security and authenticity exist in the field of water conservancy digital twin simulation. An innovative technology [78] combines blockchain and smart sensors to establish a blockchain network for water conservancy projects, realizing real-time collection, transmission and monitoring of water conservancy service data, ensuring that data cannot be tampered with and traceability, and meeting the needs of multi-party collaboration and real-time monitoring. Another technology [79] inputs digital scene data and hydraulic service data into the blockchain module, realizes intelligent perception of hydraulic service data by using intelligent sensors, and establishes a data flow mechanism by using a distributed ledger to enhance data credibility and authenticity. These technologies ensure high reliability and fidelity of data through blockchain, realize data exchange and sharing, and ensure the security of water conservancy digital twin data links.

4. Application Status

4.1. Water Security

The application of modern information technology plays a key role in real-time monitoring, rapid early warning and efficient management of water emergencies and related problems in water safety management. Taking the Sumjin Dam and river water management platform as an example, digital twin technology has been used to achieve dam safety assessment and river stability assessment, and the monitoring and safety management capabilities have been improved by combining a high-performance UAV monitoring system and video analysis system [80]. In terms of optimization of the flood prediction model, the online optimization method driven by knowledge and data fusion has realized dynamic updating of flood feature quantity and intelligent adjustment of the parameter rate, effectively improving forecast accuracy and response speed [81]. The real-time detection method of data quality of intelligent water conservancy digital dual-basin construction based on flow computing solves the problem of insufficient monitoring of data quality, and ensures the reliability and accuracy of monitoring data through the real-time quality detection of the traffic processing system Flink [82]. Through comprehensive data collection and real-time monitoring, the intelligent water conservancy early-warning management system based on digital twins improves the accuracy and timeliness of water conservancy facility management, reduces management risks and saves labor costs, thus effectively avoiding the occurrence of water conservancy facility safety accidents [83].

4.2. Water Resources

Traditional water resources management methods have problems such as delayed management decision-making and insufficient data processing technology [84]. In recent years, digital twin water network technology came into being. By quickly building the accurate and efficient digital twin water conservancy model, the dynamic visual management of the water network can be realized, and the situation of insufficient static data collection and model accuracy in the past can be solved [85]. One study [86] sorted out the physical water network elements through the design and establishment of a tetrahedral model of a digital dual water network. The authors constructed the information structure and conceptual model of the water network, and established the flow information structure and data model according to the data structure of the water network, thus realizing the digital mapping and business intelligent simulation of the water network, and providing new ideas and methods for the management of digital water networks. Another study [87] adopted the data-driven branch point processing method of digital dual water networks. Through the collection and processing of river fulcrum form data and computational fluid dynamics (CFD) simulation calculation, it solved the problems such as the lack of data drive in the hydraulic engineering fulcrum hydrodynamic calculation and prediction, and realized accurate hydrodynamic data acquisition and prediction. In terms of water network planning and construction, the water network navigation system provides comprehensive support, including the map module, supply and demand balance analysis module, path analysis module, and information retrieval and query module, and provides powerful auxiliary and platform support for water network planning and digital twin water network construction [88].

4.3. Water Conservancy Project

The intelligent application of hydraulic engineering covers intelligent monitoring, intelligent inspection and digital modeling. The intelligent monitoring method of hydraulic engineering based on digital twins [89], through the construction of the digital twin model of hydraulic engineering construction for simulation and analysis, determines the accurate emergency plan on the basis of the minimum emergency risk, and its advantage lies in the realization of the automatic monitoring and emergency response of the intelligent monitoring system for hydraulic engineering safety. The digital twin hydraulic engineering safety monitoring system [90] realizes monitoring data acquisition and feedback by connecting virtual entities, improves real-time monitoring, early warning and decision support capabilities, realizes real-time monitoring, analysis and prediction of hydraulic engineering operations, provides accurate decisions, and supports intelligent operation and reliable maintenance. In terms of intelligent inspection, BIM and knowledge map-based methods have innovatively solved past inspection problems, established an intelligent perspective inspection BIM coding model and knowledge map, and improved the level of hidden danger detection, monitoring and early warning [91]. As for digital modeling, there are some problems in the application, such as complex data preparation steps and model processing. One study [92] proposes to use photographic equipment to take 360° rotating photos of the reservoir site, modify and design the acquired data through 3D model tools, design model attributes and events combined with digital twin construction tools, and finally build an intelligent water conservancy digital twin model, which simplifies the steps of data preparation and improves the accuracy of the reservoir model. It also supports simple processing and virtual combination of models. In general, the application of digital twin technology provides important support for the intelligent development of water conservancy projects. Through the integration of GIS data, the two-way linkage between the system interface and digital display scene is realized, which promotes intelligent development [93].

5. Challenges and Countermeasures

5.1. Data Issues and Privacy Security

At present, the research of water conservancy big data theory and technology is still in its infancy, facing the problems of data barriers and analysis methods that have not played their advantages. In order to achieve scale benefits of water conservancy big data, water conservancy authorities need to organize governments, enterprises, universities and scientific research institutions to cooperate and jointly promote the healthy and orderly development of water conservancy big data [94]. In recent years, the digital watershed has developed into a smart watershed. The key technology is to use a wireless sensor network to realize the construction of a smart watershed. The wireless sensor nodes of automatic measurement and reporting rain stations, weather stations and hydrology stations play an important role in obtaining hydrological data, and optimizing the layout has become a research hotspot and difficulty in smart basin IoT, especially under the influence of global climate change and human activities [95].

An intelligent water conservancy system involves a large number of sensitive data, such as water level, water quality, hydrology and other information, and the leakage, tampering and malicious attack of these sensitive data may lead to disastrous consequences. Therefore, it is necessary to strengthen data encryption, permission control, security monitoring and other measures to ensure the confidentiality, integrity and availability of data. For the protection of user privacy, the system needs to design a reasonable access control mechanism to ensure that only authorized personnel can access specific data. At the same time, establishing a security audit mechanism to monitor the access and use of data and detecting abnormal behaviors in a timely manner are also required.

5.2. Technology Integration and Talent Innovation

The digital twin model should not only accurately map the physical entity characteristics obtained by mapping, but also accurately reflect its behavior rules and interaction mechanisms. Because the mapping data may not be complete, detailed or timely, inference needs to be made with the help of model knowledge. The construction of a spatial-temporal knowledge center still faces challenges, and cross-border integration needs to introduce artificial intelligence and knowledge engineering talents to solve the shortcomings of talent training, knowledge reserve and core technology. There is a need to build an ecosystem of spatio-temporal data on natural resources and provide knowledge empowerment services to support accurate decision making and intelligent management and control [74].

Therefore, one of the important challenges of digital twin modeling is to organically integrate real-time 3D data with mechanism models and expert experience [96].

5.3. Standardization and Normalization

The smart water conservancy platform lacks standard references such as an information infrastructure, data base, model platform, knowledge platform and business application, resulting in difficulties in the integration of the water conservancy model and data and knowledge, and weak system compatibility and interoperability, resulting in the phenomenon of data, knowledge and model island and system chimney [97]. The water conservancy data base also lacks the guidance of data classification and representation, data organization, data fusion, data service and other standards. The digital twin water conservancy model platform is the core engine of intelligent water conservancy. Currently, there is a lack of standards for model classification and representation, model encapsulation, model storage, model assembly, etc., resulting in the situation of useless models, although there are many models. Due to the lack of guidance on the classification and representation of water conservancy knowledge, storage of water conservancy knowledge, integration of water conservancy knowledge and other standards, the digital twin water conservancy knowledge platform still lacks an available business knowledge base in the water conservancy field [29].

At present, the construction of smart water conservancy standards is still in its initial stage, lacking perfect organization, research and application. When examining the digital twin intelligent water conservancy framework in this paper, it can be seen that the current progress of standardization is still lagging behind. Although the framework envisions a layered structure that includes a perception layer, a network layer, a platform layer and an application layer, the effectiveness of this layered structure is hampered by the lack of standardized processes and organizational structures. In order to realize the sustainable development of smart water conservancy, the standardization process should be promoted [29]. It is necessary to make full use of the existing advantages of basic research, promote interdisciplinary development, and continuously improve the standard system of the water conservancy industry [98], so that it can take a leading position in the world in multiple fields of water conservancy science and technology. Other key measures include: government support [99], top-level design and prioritization of key standards [100], selection of standards advocacy and implementation strategies, and efficiency orientation.

6. Summary and Prospect

The smart water conservancy system based on digital twins uses a new generation of information technology to build data and model integration methods to realize real-time monitoring, analysis and decision-making of water conservancy management. On the basis of previous studies, the framework of the intelligent water conservancy system based on digital twins is proposed, but future research should focus on the challenges that may be faced in the verification process, such as data security, complexity of system integration and technical standardization. This study summarizes its core technologies including integrated monitoring, big data and artificial intelligence, cloud network integration, digital twin platforms, knowledge graphs and blockchain security technology, which are widely used in water security, water resources and hydraulic engineering. These technical frameworks and methodologies promote the transformation of the water conservancy industry from traditional management to intelligent management, and ensure the sustainable use and security of water resources. By integrating a variety of advanced technologies, real-time monitoring and accurate management of water conservancy systems can be realized, resource allocation can be optimized, flood prevention early warning and water quality management efficiency can be improved, safety and reliability of water conservancy projects can be enhanced, and the scientific basis for policy formulation can be provided.

Future smart water conservancy construction is benefiting from the rapid development of new monitoring methods and cutting-edge technologies. With the help of the Beidou Communication remote air and earth monitoring system, 6G + IPV6 Internet system and water remote sensing satellite, all-round water resources monitoring and data collection can be achieved. Deep integration of the physical watershed and virtual (or digital) watershed in the construction of the digital twin watershed model is regarded as the core of future research. The digital twin virtual model driven by data, mechanism and knowledge is constructed. Promoting independent research and development of large water conservancy models, and applying domain training and knowledge graph technology is required to achieve advanced, practical, integrated, open, reliable and safe large water conservancy models [101]. These models not only have core capabilities, but also can play an important role in various “2 + N” business scenarios, resulting in the establishment of a large water conservancy model system that is co-built and shared. In addition, the construction of the coupling system of scientific prediction, early warning, rehearsal and preplan is also an important part of future smart water conservancy. Combined with the smart security protection system based on the cryptographic mechanism, the innovative integration of cryptographic technology, security situational awareness and dynamic defense technologies will provide a safe and reliable guarantee for smart water conservancy and promote the sustainable development of the field. These measures will certainly bring about a qualitative leap in the assessment, prediction and management of global water resources, and promote the development of smart water conservancy in a more intelligent and efficient direction.

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