Research on the Construction of the Yellow River Smart Ice Prevention Application

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ABSTRACT Reliable monitoring and forecasting of large-scale environmental hazards require efficient sensing, robust information transmission, and intelligent analysis of heterogeneous spatiotemporal data. This study proposes a smart ice-prevention framework for the Yellow River based on distributed sensing networks, digital twin technology, and multi-source information fusion. A hierarchical architecture integrating monitoring and perception networks, communication infrastructure, cloud-based computing resources, and digital twin platforms is developed to support real-time acquisition and management of hydrological, meteorological, and ice-condition information. To improve situational awareness and forecasting capability, heterogeneous data from ground sensors, video monitoring systems, unmanned aerial vehicles, and remote-sensing platforms are fused through a multidimensional spatiotemporal data model. Machine-learning-based prediction models, pattern-recognition algorithms, and knowledge-driven reasoning mechanisms are further employed to achieve ice-condition forecasting, early warning generation, and emergency-response support. Experimental deployment demonstrates that the proposed framework significantly enhances monitoring efficiency, forecasting accuracy, and decision-support capability for ice-prevention operations. By integrating distributed sensing, spatiotemporal information fusion, digital twin modeling, and intelligent forecasting, the proposed framework provides an effective methodology for large-scale monitoring systems, environmental sensing networks, and data-driven hazard management in complex dynamic environments.

INDEX TERMS distributed sensing networks, remote sensing monitoring, spatiotemporal information fusion, digital twin modeling

I. OVERVIEW OF YELLOW RIVER ICE PREVENTION

Ice flood, commonly known as ice floes, is a hydrological phenomenon in which the water level of a river rises significantly due to the resistance of ice to the flow of water. Ice can sometimes gather into ice jams or ice dams, causing the water level to rise significantly, eventually flooding the beach or breaking the embankment, which is called ice flood [1]. The Yellow River Basin is located north of the geographical and climatic dividing line between the Qinling Mountains and the Huaihe River, and is in the transition zone where ice conditions occur in the northern rivers of my country in winter. The Yellow River Basin spans 23 degrees of longitude from east to west and 10 degrees of latitude from north to south [2]. Therefore, in winter, some sections of the upper, middle and lower reaches of the Yellow River are frozen. Since the water flow in the upper Ningmeng River section and the lower Shandong River section flows from low latitudes to high latitudes, there is a temperature difference between the beginning and end of the river section, resulting in different times of river closure and opening, with the river closing from the bottom up and opening from the top down. The formation of ice floods in these sections is driven by complex hydraulic and thermodynamic coupling. Specifically, an ice jam (冰塞) typically occurs during the freeze-up period when frazil ice, generated by intense heat loss from the water surface to the cold atmosphere, is transported under the ice cover. When the hydraulic transport capacity of the flow is insufficient to carry the incoming ice, it accumulates at sections with reduced velocity (such as bends or bridge piers), increasing hydraulic resistance and significantly raising the water level. In contrast, an ice dam (冰坝) is primarily a mechanical pr ocess during the break-up period. As temperatures rise, the in ternal thermal strength of the ice cover weakens, leading t o its fracture. Large ice floes are then driven downstream by the increasing discharge; they may become structurally wedged in narrow or shallow sections, forming a physical blockage that exceeds the river's driving force and causes a rapid, catastrophic rise in stage. This unique situation easily forms ice jams or ice dams, thus causing ice floods, threatening the lives and property of residents along the river and the safety of river water conservancy projects. Affected by factors such as geographical location, river direction and river channel conditions, the Ningmeng River section and the lower reaches of the Yellow River are key sections for ice disaster prevention and control [3]. Since the people's control of the Yellow River, relatively complete non-engineering protection measures for the Yellow River have been basically established. Since 2000, the Yellow River Conservancy Commission has successively built the Yellow River Flood and Ice Decision Support System and other information applications, effectively supporting ice prevention management while safeguarding the water security and industrial stability of the regional industry through enhanced information supervision and dispatching. In July 2019, the Ministry of Water Resources officially issued the "Overall Plan for Smart Water Conservancy," which clarified the overall requirements, overall architecture, key tasks, and organizational implementation methods for smart water conservancy development. Since 2021, at the summary conference of the "Three Benchmarks, One Planning" special action plan, the Ministry of Water Resources has clearly stated: "With digitalization, networking, and intelligence as the main lines, we will build digital twin river basins, conduct intelligent simulations, support precise decision-making, comprehensively advance the development of computing data, algorithms, and computing power, and accelerate the construction of a smart water conservancy system with forecasting, early warning, rehearsal, and emergency plans (hereinafter referred to as the "four preplanning") capabilities." The relevant specifications such as the "Technical Outline for Digital Twin Basin Construction (Trial)", "Technical Guidelines for Digital Twin Water Conservancy Project Construction (Trial)", and "Basic Technical Requirements for the "Four Pre-production" Functions of Water Conservancy Business (Trial)" further clarified the content of digital twin basin construction [4], proposed a technical route for achieving smart water conservancy goals through digital twins and "four pre-production", and refined and clarified the requirements for what to build, who to build, how to build, and how to share digital twin basins, digital twin water networks, digital twin water conservancy projects, and "four pre-production" work, providing basic technical guidelines for the construction of smart water conservancy by water conservancy departments at all levels. Compared with the digital twin and "four-prediction" work requirements of the Ministry of Water Resources, there are certain gaps in the existing relevant ice prevention information systems. The Yellow River Flood and Ice Prevention Decision Support System was built in 2005. The system adopts a C/S architecture and can provide water, rain, construction conditions and other information services for flood and ice prevention consultation and decision-making [5]. Due to the early construction time of the system, the system architecture and performance can no longer meet the current needs of the Yellow River Conservancy Commission's ice prevention management work, and it does not have the support capabilities for ice situation warning, rehearsal and emergency plan. The Yellow River Upper Reaches Flood and Ice Prevention Dispatching System of the National Flood Control and Drought Relief Command System Project serves the Yellow River ice prevention dispatching work, and its management scope covers the upper reaches of the Yellow River. From the perspective of the Yellow River Conservancy Commission's ice prevention management work, the system has incomplete coverage and cannot fully support ice prevention consultation and other work, and does not have warning and rehearsal functions. The Yellow River Flood and Ice Prevention Dispatching Decision Consultation System is based on the SOA holographic management architecture and uses multi-source data fusion technology to build a three-dimensional landform platform for the basin. Combined with the consultation business process, it fully covers the consultation themes such as daily flood prevention consultation, flood prevention deployment consultation, flood dispatch plan consultation, major dangerous situation rescue consultation, emergency event consultation and ice prevention consultation, and realizes the full process and full stage management of the Yellow River flood prevention consultation process [6]. However, the system still cannot support the demand for ice situation warning and rehearsal functions in the Yellow River Conservancy Commission's ice prevention management work. The Yellow River flood control consultation and rehearsal system, as a typical application of the Ministry of Water Resources' overall deployment of the "four predictions" of informatization in the Yellow River Conservancy Commission, was put into operation in June 2022. The system serves the Yellow River flood control consultation work during the flood season. Aiming at the key links of the Yellow River flood control consultation work, a comprehensive consultation and decision-making system with "early warning, forecast, rehearsal, and emergency plan" functions has been built, which effectively improves the Yellow River Conservancy Commission's modern consultation and management capabilities for flood and drought disaster prevention [7]. In response to the shortcomings of the Yellow River Conservancy Commission's existing ice prevention information application "four predictions" functions, in October 2022, the Party Committee of the Yellow River Conservancy Commission proposed the work requirements of supplementing and improving the smart ice prevention functions on the basis of the existing Yellow River flood control consultation and rehearsal system. Based on the Yellow River flood control consultation and rehearsal system, existing ice prevention resources are integrated and upgraded to meet smart water conservancy and "four predictions" requirements, ensuring more reliable water resource allocation and disaster mitigation for the regional industry.

II. APPLICATION SYSTEM CONSTRUCTION

A. GENERAL LAYOUT

The system construction adheres to the overall framework of the top-level design for smart water conservancy, integrates the current status of the Yellow River Conservancy Commission's ice prevention management and informatization work, and is based on the existing Yellow River flood control consultation and rehearsal system, in accordance with the requirements for effectively supporting smart ice prevention work on the Yellow River. The overall framework is shown in Figure 1. The Yellow River Smart Ice Prevention Informatization Application System construction framework consists of seven components: the physical Yellow River, infrastructure, digital twin platform, smart applications, network security system, Yellow River Conservancy Commission cloud platform, and technical standards and assurance system. The network security system provides security management, protection, and oversight support for the Yellow River Smart Ice Prevention informatization application, and provides reliable network security assurance for other system components. The standards and assurance system supports system construction with technical standards and specifications, institutional mechanisms, operation and maintenance systems, standardized management, talent pool, and publicity and communication. The Yellow River Data Center cloud platform provides reliable computing power for the system. Physical management objects are the target objects for the construction and management of the Yellow River Smart Ice Prevention informatization application. They represent the "digital mapping" of real-world entities, ice prevention-related water conservancy objects, events, and the impact areas of ice conditions. Infrastructure ensures the system's ability to perceive, acquire, and transmit data. The Yellow River Data Collection and Perception Network is a channel and means for acquiring comprehensive, authentic, objective, and dynamic water conservancy data and information from the physical world. The Yellow River Information Network serves as the carrier, network channel, and supporting network infrastructure for the transmission of various water conservancy information systems within the Yellow River Conservancy Commission. The foundational support provides public system functional service support for other construction projects. The ice prevention data backplane provides a unified digital landscape for ice prevention management. The model platform focuses on business development goals and provides algorithmic support with "four prediction" capabilities. Unlike general flood models, this platform prioritizes ice-specific evolution logic, integrating specialized hydraulic-thermal coupled algorithms to simulate frazil ice transport and ice cover thickening processes, which are essential for accurate ice flood forecasting. The knowledge platform aggregates various ice prevention-related knowledge, forming a unified ice prevention knowledge base for the Yellow River Conservancy Commission (YRCC). This knowledge base provides essential historical experience and expert advice for ice prevention management. The data platform provides visualization capabilities for digital scenarios of Yellow River ice prevention, while the foundational support, modeling platform, and knowledge platform underpin the system's intelligent simulation capabilities. The digital twin of the Yellow River basin, based on the "ice prevention" theme, provides algorithms and data support for precise ice prevention decision-making in flood and drought prevention applications such as the Yellow River Flood Control Consultation and Rehearsal System. The development of intelligent applications for ice prevention builds on the existing Yellow River Flood Control Consultation and Rehearsal System, supplementing and improving its functionality. To avoid redundancy, a clear logical boundary is established: the existing flood system provides the 'general-purpose' engine (GIS mapping, user management, and communication protocols), while the ice prevention application is implemented as a specialized 'thematic plugin.' This ice prevention module focuses exclusively on unique winter variables—such as frazil ice density, ice dam mechanics, and thermal thermodynamics—which are logically decoupled from the rainfall-runoff models used in general flood prevention. Integrate the existing achievements in the application of ice prevention information technology, build ice prevention monitoring, ice prevention warning, ice prevention surveillance and ice prevention plans, etc., realize the monitoring of water temperature and air temperature, ice flow, ice thickness, water and rainfall conditions, trough water storage, reservoir water storage, etc., as well as online call and data analysis of various existing ice prevention dispatching, duty, emergency plans, ice prevention theme model platforms and knowledge bases, realize the prediction of water and rainfall conditions, air and water temperature, ice flow, river closure, etc., early warning reminders of potential ice conditions, simulation preview of river closure, ice flow, reservoir ice prevention dispatching scenarios, as well as automatic generation and recommendation of ice prevention project dispatching, emergency rescue plans.

B. PHYSICAL IMPLEMENTATION

The development of the Yellow River Smart Ice Flood Prevention information technology application primarily involves building computing power, data processing, algorithm services, and the construction of the smart ice flood prevention application. The technical implementation of each component involves the following work steps, as shown in Figure 2. Building computing power primarily encompasses monitoring and perception, communication networks, and the Yellow River Cloud, a Yellow River Data Center. Sensors are used to collect data on water and rainfall conditions, air and water temperatures, and ice flooding. Key sections and projects in the basin are monitored and monitored via video. New technologies such as drones and remote sensing satellites are used to remotely monitor river closures and ice flow in the basin. Self-built and leased information transmission channels, as well

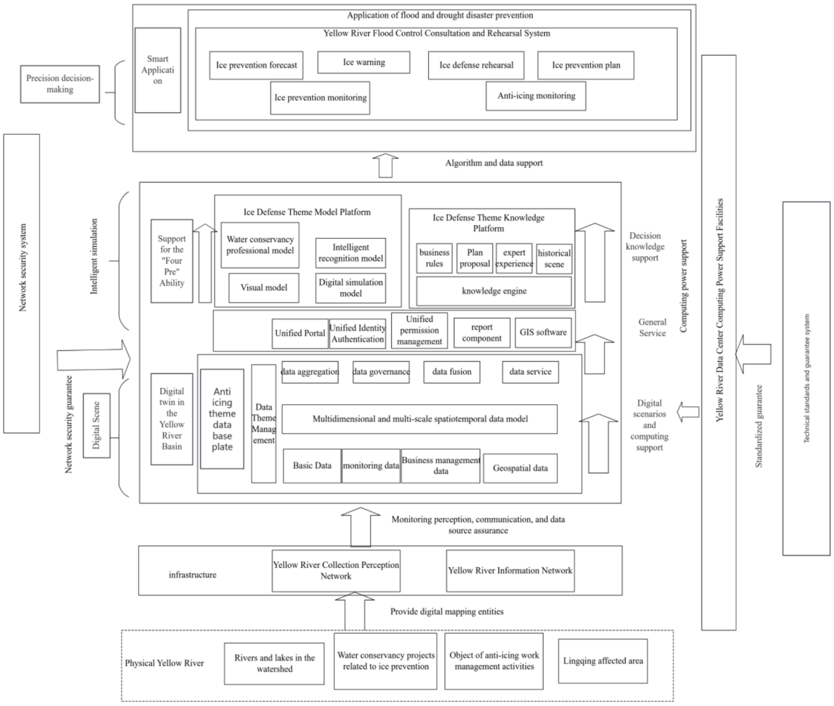

FIGURE 1. Yellow River Smart Ice Flood Prevention Information Support Application System Architecture

as the Yellow River Conservancy Commission's existing network and security infrastructure, provide network access and security for various software, hardware, and data resources. The Yellow River Cloud, based on the Yellow River Data Center, provides reliable computing and storage services for the Yellow River Smart Ice Flood Prevention application. The construction of a data backend provides computational support for the Yellow River Smart Ice Prevention information technology application. This includes data aggregation and governance, as well as digital scenario construction. The digital twin data backend, encompassing basic, geospatial, monitoring, and business data resources, is extracted and aggregated through databases, services, and file extraction. Data mapping establishes relationships with water conservancy objects. After data governance, data is cleansed and removed. The results of data governance are centrally stored in a cloud platform database for existing data resources. The construction of a multidimensional, multi-scale spatiotemporal data model includes technologies such as water conservancy object modeling, relationship building between scenarios and objects, between objects, and between data and objects, and 2D and 3D scenario construction. Object modeling enables entity modeling of water conservancy objects in the real world. Utilizing 2D scenario construction, a multi-scale 2D cartographic framework is established, ranging from macro-level basin overviews (L1) to high-precision thematic maps (L3), in accordance with digital twin technology requirements. Utilizing 3D scenario construction, multi-fidelity 3D digital landscapes are developed across Level-of-Detail (LoD) 1 to 3, providing a seamless transition from low-polygon regional terrains to high-definition engineering-grade visualizations in accordance with digital twin technology requirements. By employing semantic relationship mapping between scenes and objects, between objects, and between data and objects, the system achieves deep integration of heterogeneous datasets—including foundational, geospatial, monitoring, and cross-sectoral management data—with physical water conservancy entities across unified 2D and 3D digital environments after data governance.

The construction of algorithm services includes: model services, knowledge services, basic services and functional encapsulation services, which provide algorithmic capability support for the ice prevention theme of the Yellow River flood prevention consultation and rehearsal system. Model services include mechanism analysis and prediction, data-driven prediction, pattern recognition, simulation and visualization services. To address the unique challenges of ice floods, the model service layer incorporates a specialized Ice Evolution Engine. This engine optimizes traditional hydrodynamic equations by embedding ice-water heat exchange coefficients and mechanical strength parameters for ice covers, enabling the system to specifically simulate the transition from stable ice cover to mechanical breakup (ice dam formation) rather than just general water level fluctuations. The knowledge service mainly includes knowledge extraction, knowledge base construction, knowledge reasoning, knowledge discovery and rule engine and other work links during the construction process. Basic services include security authentication, report components, GIS

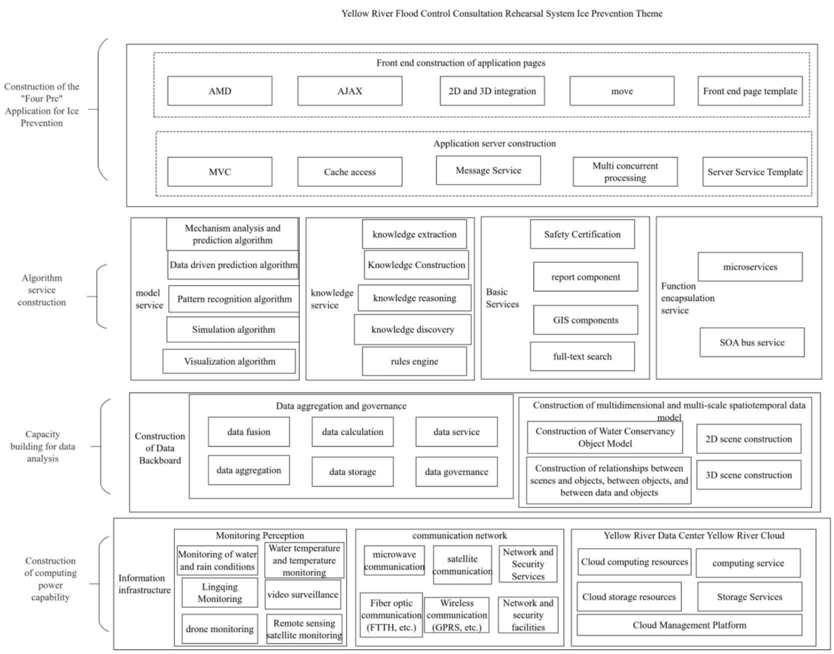

FIGURE 2. Yellow River Smart Ice Flood Prevention Information Support Application Technology Implementation Principle

components, full-text retrieval and other service contents. Data services provide a unified data resource access interface for various applications, including two service types: SOA bus services and microservices. Data that requires coordinated time series processing and collaborative cooperation is encapsulated using SOA bus services, and other types of data are encapsulated using microservices. The construction of the smart anti-ice application mainly includes two aspects: the construction of the business application server and the construction of the business application front-end. The logical architecture distinguishes between the 'Shared Service Layer' (general flood data) and the 'Ice Business Logic Layer.' The former handles multi-source data fusion for river geometry, while the latter specifically invokes specialized ice-regime algorithms and forecasting scripts that are only activated during the winter ice period, thereby ensuring that the ice prevention modules do not interfere with or duplicate the standard flood prevention workflows. The server construction involves the construction of the server MVC framework, cache access, message service, multi-concurrency processing, etc. The front-end construction involves the construction of the page front-end modularization (AMD) framework, AJAX back-end service calls, 2D and 3D integrated digital scene display, mobile terminal display and the construction of the front-end page template.

III. KEY TECHNOLOGIES

The key and difficult issue in the construction of the Yellow River Smart Ice Prevention Application System is how to implement the "four prediction" functions based on the characteristics of the Yellow River ice prevention business. To this end, the following solution is proposed. The key technologies and implementation principles are shown in Figure 3.

A. CONSTRUCTION OF ANTI-ICING THEME DATA BASE

The data base is the foundation for the system to realize the "four prediction" functions. Multi-source data fusion technology is used to collect and organize relevant basic, geographic space, monitoring, business management and cross-industry shared data, build a multi-dimensional and multi-scale spatiotemporal data model, and use water conservancy object entities as the basic unit of data expression and classification organization. To address the heterogeneity between satellite remote sensing and ground sensors, a unified spatiotemporal matching logic is implemented. Specifically, spatial registration is achieved by projecting multi-source data onto a standardized CGCS2000 coordinate system, while temporal alignment utilizes a hierarchical resampling strategy that maps high-frequency ground sensor streams and periodic satellite observations onto a synchronized time axis. This allows the system to integrate and reorganize various types of data with spatiotemporal attributes as the link, and realize the construction of a multi-level nested spatiotemporal data base [8]. Multi-source data fusion technology can realize the fusion and governance of a large amount of heterogeneous data of different units, different formats, different structures and different qualities, ensuring that disparate data sources are geometrically and temporally consistent before being integrated into an organic whole [9]. Compared with traditional multi-source data fusion technology, when constructing the anti-ice theme data base, the water conservancy objects such as river basins,

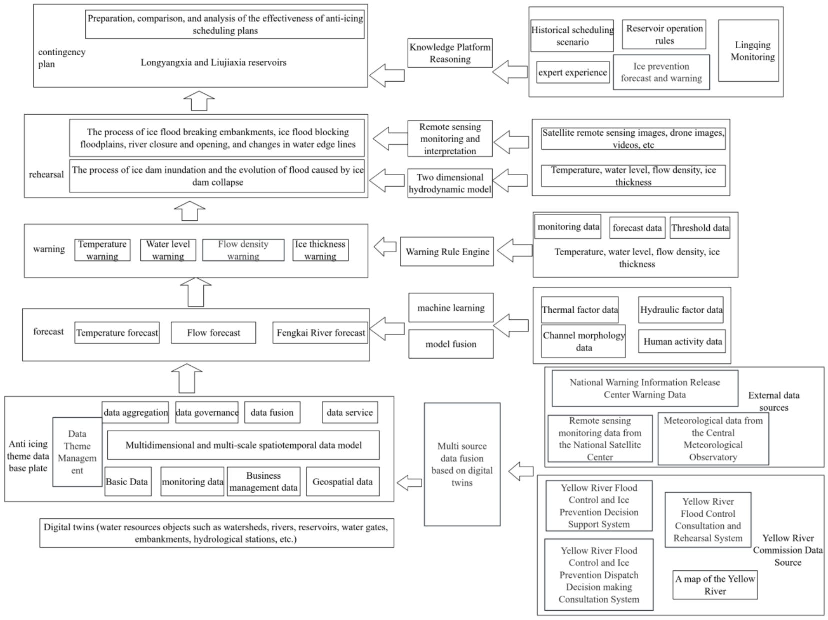

FIGURE 3. Yellow River Smart Ice Flood Prevention Application System Key Technologies and Implementation Principles

rivers, reservoirs, sluices, and embankments in the system are digitized into digital twin objects. These water conservancy digital twin objects are defined through the RDF data model. The model definition includes the basic attribute information of the water conservancy digital twin object, two-dimensional geographic information, three-dimensional and BIM information, monitoring information, business information and cross-industry related information (Note: various types of information are encapsulated in the form of Rest services). In addition, the water conservancy digital twin models are associated through relationship attributes such as space (such as upstream and downstream), time (such as different years), management (such as management and being managed), and cause and effect (such as influence and being affected), and different water conservancy digital twin models are subject-classified and managed according to the working habits of water conservancy business management. Compared with traditional multi-source data fusion technology, the multi-source data fusion technology based on water conservancy digital twins has the characteristics of triples, so it is highly flexible and scalable. In addition, storing RDF data in the graph database Neo4j has the characteristic of fast retrieval speed compared to other data fusion solutions.

B. ICE FORECAST CONSTRUCTION

Machine learning technology is used to achieve ice forecasting, and the model prediction accuracy is improved through integrated learning technology. Machine learning is a discipline that studies how to use computers to simulate or realize human learning activities. It is an important foundation for knowledge discovery, data mining and other fields [10]. In the water conservancy industry, machine learning technology has been widely used in precipitation forecasting, runoff forecasting and other fields [11]. During the construction of the system, according to the requirements of the Yellow River ice prevention work, thermal factor data (such as air temperature, water temperature), hydraulic factor data (such as water level, flow, channel water storage increment, etc.), river morphology data (longitudinal gradient, curvature, etc.) and human activity data (such as reservoir project ice prevention scheduling plan, etc.) were extracted from the data base. Using support vector machines, neural networks, time series and other model algorithms, medium- and short-term forecasts were made for the development trends of air temperature, ice flow and river closure in the key ice prevention sections of the upper and middle reaches of the Yellow River. Ensemble learning aims to improve the accuracy of automatic decision-making systems [12]. In order to enhance the accuracy of model prediction, the Bagging algorithm in ensemble learning technology is used to train the ice forecast data set. To verify the system's effectiveness, backtesting was conducted using historical ice flood event data from 2010 to 2022. The model was evaluated based on its ability to predict critical freeze-up dates and ice thickness. After training, the forecast results of different models are generated. By comparing the integrated output with actual historical observations, the results showed that the ensemble approach reduced the Mean Absolute Error (MAE) by 12% compared to single-model forecasts, achieving a prediction accuracy of over 85% for key river sections. These results are averaged using the averaging method, and the average value is used as the result of ice forecast.

C. ICE FORECAST ALARM CONSTRUCTION

In traditional information systems, early warning information can be implemented by programming a script in a development language to compare with the warning threshold. Compared with traditional development technology, rule engine technology has the characteristics of easy maintenance of warning rules and strong real-time processing capabilities. Zhang X et al. [13] proposed an early warning indicator system for ice flood disasters in the Ningmeng section of the Yellow River based on the causes and ice conditions of the Yellow River. When the system was constructed, the relevant monitoring, forecasting and threshold data such as temperature, water level, ice density and ice thickness of the upper and middle reaches of the Yellow River were extracted from the ice prevention theme data base. The drools tool was used to build an ice prevention early warning rule engine. The rule engine was used to standardize the early warning rules for temperature, water level, ice density and ice thickness. The temperature, water level, ice density and ice thickness data of the relevant river sections monitored and forecasted were written into the rule engine through the scheduled task queue to dynamically generate ice warning information.

D. CONSTRUCTION OF ICE PREVENTION REHEARSAL

During the Yellow River ice flood season, remote sensing monitoring and interpretation are generally used weekly to monitor the closure and opening of the river and changes in the waterfront in key sections of the upper and middle reaches of the Yellow River. These monitoring results are overlaid on the ice prevention digital scene as a 2D vector layer service. By selecting the interpretation results at different time points along the timeline, the changes and developments in the closure and opening of the river and the waterfront in the river section of interest can be clearly observed. During ice flooding events, remote sensing monitoring and interpretation are used daily to dynamically monitor the occurrence and development of dangerous events such as ice flooding, dike breaches, and floodplains. These monitoring results are overlaid on the ice prevention digital scene as a 2D vector layer service. Dynamic scrolling through the timeline allows a clear understanding of the entire process of ice flooding, effectively supporting emergency rescue efforts. The Shisifenzi section of the middle Yellow River, a section prone to ice flooding, has historically been a top priority for ice prevention efforts. To this end, the Yellow River Smart Ice Prevention Application System selected this section as a pilot project during its construction. A two-dimensional ice-water dynamics model was established around the 60km section above and below Toudaoguai. The model calculated the ice-dam inundation process and the evolution of ice dam breach floods at different locations (bridges, bends) and flow rates in the river section. Based on the ice prevention digital scenario, the process of ice flow and ice thickness changes upstream and downstream of Toudaoguai was rehearsed.

E. CONSTRUCTION OF ANTI-ICE PLAN

The knowledge platform uses technologies such as knowledge graphs and machine learning to extract, manage and combine knowledge such as the association relationship between water conservancy objects and water conservancy laws, providing an intelligent core for the digital Lisheng River Basin and supporting forward intelligent reasoning and reverse causal analysis [14]. During the construction of the system, the knowledge platform reasoning technology was used to realize the function of compiling reservoir anti-ice scheduling plans. The knowledge platform consists of two parts: the knowledge base and the knowledge engine. During the construction process, the knowledge base aggregated and integrated the historical scheduling scenarios of river basin anti-ice scheduling, reservoir anti-ice application rules and reservoir anti-ice scheduling expert experience through the data base. The knowledge engine organizes the knowledge base data and compares the historical monitoring, forecast and warning data based on the current ice monitoring, forecast and warning data by calling similarity analysis algorithms such as KNN and correlation analysis algorithms, thereby inferring the anti-ice scheduling plan with the highest correlation or similarity and recommending it. In addition, the system also realizes the functions of comparative analysis between different scheduling plans and comparison between scheduling plans and actual scheduling implementation, thereby ensuring the scientific nature of the scheduling plan and providing a reliable information support tool for the superior anti-ice scheduling unit of the Yellow River Conservancy Commission to supervise the implementation of the anti-ice scheduling work of the subordinate units.

IV. APPLICATION EFFECT

Construction of the Yellow River Smart Ice Prevention System, based on the Yellow River Flood Control Consultation and Rehearsal System, began in October 2022. Through the concerted efforts of all relevant units involved in ice prevention work at the Yellow River Conservancy Commission (YCC), it officially launched in February 2023. The system aggregates relevant digital resources related to ice prevention from all units of the YCC. In accordance with the Ministry of Water Resources' digital twin technology requirements, the system has built an ice prevention-themed data platform, enabling the aggregation, governance, sharing, and provision of services for basic, geospatial, monitoring, and operational data resources related to ice prevention. Based on the "Yellow River One Map," a digital ice prevention scenario has been constructed, effectively integrating relevant information on air temperature, water temperature, water conditions, ice conditions, scheduling, emergency plans, and remote sensing. The model platform integrates data from models such as the two-dimensional ice-water dynamics model, the ice disaster loss assessment model, and the ice flood season reservoir joint scheduling model. The knowledge platform integrates historical ice prevention scheduling plans, emergency plans, scheduling rules, and legal and regulatory information. Based on the existing functions of the Yellow River flood control consultation and rehearsal system, the monitoring, surveillance, and forecasting of temperature and ice conditions were achieved. The online display, flood control calculation, and compilation and confirmation of ice control scheduling plans for reservoirs such as Longyangxia and Liujiaxia were also achieved. A two-dimensional ice-water dynamics model was established around the 60km area above and below Toudaoguai. The inundation process of ice jams and dams at different locations (bridges, bends) and different flow rates, as well as the evolution of ice dam breach floods, were calculated. The process of ice flow and ice thickness changes upstream and downstream of Toudaoguai was rehearsed.

V. SUMMARY AND PROSPECTS

The construction of the Yellow River Smart Ice Prevention Application System follows the logic of smart water conservancy to promote high-quality development, utilizing digital twins and artificial intelligence to ensure precise water dispatching that safeguards the production stability of the regional industry. By integrating the "four pre-emptive measures," the system provides the data-driven security necessary for manufacturing facilities to mitigate ice-related water supply risks and maintain operational continuity. During the system construction process, the framework of the Yellow River Conservancy Commission’s ice prevention smart application system was designed and proposed, and based on this, a typical smart water conservancy application for professional ice prevention work in the Yellow River Basin was initially established. After the application system was completed, it strongly supported the 2023 Yellow River ice prevention consultation work, built a special ice prevention data base, and achieved comprehensive supervision of the ice prevention work of the entire river through the system, enhanced the "four pre-emptive measures" support capability of the Yellow River ice prevention work, improved the efficiency of ice prevention consultation work, and reduced the economic and time costs caused by poor information flow. Currently, the Yellow River Conservancy Commission is coordinating the information resources of the Resource Satellite Application Center and other units, leveraging the advantages of resource integration, upgrading digital scenarios, and continuously refining the construction of the L2-level data base for the basin, further enhancing the system’s two- and three-dimensional integrated rehearsal and simulation capabilities. In addition, relevant system specifications are being improved, and relevant systems and management methods are being introduced. In the next stage, the clarification of data sources and update protocols will ensure the Yellow River flood control consultation and rehearsal system remains accurate, providing reliable information tools to protect the water security and industrial continuity of the regional sector. These continuous data updates will facilitate precise ice prevention management, directly supporting the stable production environment required by manufacturing facilities along the river.

AUTHOR CONTRIBUTIONS

Conceptualization –Wen Du and Liangliang Li; methodology – Wen Du and Liangliang Li; investigation – Wen Du and Liangliang Li; writing-original draft preparation – Wen Du and Liangliang Li. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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