DOI: 10.54254/2977-3903/2025.21542

Research on the application of the multi-objective coordination "Four-Preparation" scheduling system in typical plain river networks: A case study of Kunshan

Jian Hu [1, a], Yiting Bo [2, b], Xingtong Chen [3, c, *]

[1]Kunshan Flood and Drought Prevention Command Office, Suzhou, Jiangsu, 215300, China
[2]Kunshan Dianshan Lake Water Area Integrated Management Center, Suzhou, Jiangsu, 215300, China
[3]Nanjing Hydraulic Research Institute, Nanjing, Jiangsu, 210000, China

a. 707418802@qq.com, b. 592154554@qq.com, c. 1192983196@qq.com
*corresponding author

Abstract. Kunshan, a typical river network city located in the Taihu Plain, has a dense network of rivers, with upstream receiving discharge from rivers and downstream supported by multiple tributaries entering the Yangtze River. Additionally, the city's internal embanked areas are numerous. Furthermore, the existing information system was constructed prematurely and lacks professional forecasting and simulation technologies, making it difficult to fully grasp the current water security situation and rapidly display the effects of scheduling plans. This study analyzes the "Four-Preparation" integration and proposes improvements. Based on Kunshan's current situation, the goal is to construct an Integrated Four-Preparation System, establishing a scientific coupling system for forecasting, early warning, rehearsal, and contingency planning. This will strengthen intelligent and smart development applications to achieve scientific disaster reduction.

Keywords: Integrated Four-Preparation System, River Network Cities, Smart Water Management

1. Introduction

Kunshan, located in the heart of the Yangtze River Delta, has a dense river network and developed water systems, making it a typical water town in the Jiangnan region. However, with the acceleration of urbanization and the intensification of human activities, Kunshan's river network faces multiple challenges, including water pollution, ecological degradation, water resource shortages, and frequent flooding. In response to these challenges and to achieve sustainable development of the river network, Kunshan has actively explored new models for river network management. The city has proposed the "multi-objective coordination and Integrated Four-Preparation System" for river network governance and conducted corresponding system application research.

In recent years, with the introduction of the concept of smart water management, intelligent management of river networks has become a research hotspot. Scholars both domestically and internationally have conducted extensive research on hydrodynamic simulation, water quality prediction, ecological assessment, and flood forecasting and early warning in river networks, achieving a series of results. For example, the DELFT-3D model developed in the Netherlands can simulate the hydrodynamics, water quality, and sediment transport processes of complex river networks, and is widely used in estuarine and coastal engineering, as well as water resource management [1]; the BASINS model developed by the US EPA integrates hydrology, water quality, and ecology models, and can be used for watershed water environmental management [2]; models such as the Taihu Basin water environment model and the Yangtze River estuary hydrodynamic model developed by Chinese scholars have also achieved good results in practical applications; the European Centre for Medium-Range Weather Forecasts (ECMWF) has developed the European Flood Awareness System (EFAS), which provides flood forecasting and early warning services globally [3]. However, existing research mostly focuses on single objectives or isolated aspects, and there is a lack of systematic research on multi-objective coordination and the integration of the four-preparation system in river network management. River network governance involves multiple objectives, such as flood control, water resource security, water environmental management, and ecological restoration. These objectives often conflict with each other, so achieving multi-objective collaborative optimization is one of the current research challenges. Additionally, the four components of the river network scheduling system—forecasting, early warning, rehearsal, and contingency planning—are interrelated and influence each other, but most current four-preparation systems operate independently, lacking effective integration, which limits their overall effectiveness. Furthermore, river network governance involves multiple departments such as meteorology, hydrology, environmental protection, and urban construction, leading to dispersed data and inconsistent standards, making it difficult to achieve data sharing and business collaboration [4]. Finally, existing models still face issues such as insufficient accuracy and poor adaptability when simulating the hydrodynamics, water quality, and ecological processes of complex river networks, making them unable to meet the demands of detailed management.

This study aims to construct a multi-objective coordination and Integrated Four-Preparation System for Kunshan’s river network and conduct application research to provide scientific evidence and technical support for river network governance in Kunshan. The main research contents include: (1) constructing a multi-objective coordination model for Kunshan’s river network to simulate and analyze the changes in hydrodynamics, water quality, and ecology under different scenarios; (2) developing an Integrated Four-Preparation Platform for Kunshan’s river network to realize real-time monitoring, forecasting, early warning, scenario rehearsal, and emergency plan management for water conditions, water quality, and ecology; (3) selecting typical areas for system application demonstrations, evaluating the effectiveness of system applications, and proposing optimization recommendations. This research is of great significance for improving Kunshan’s river network governance level, ensuring water security, and promoting water ecological civilization. The research results can also serve as a reference for river network governance in other regions.

The Integrated Four-Preparation System is the core of smart river network management, and its research can significantly improve the efficiency of river network governance. The integration of forecasting, early warning, rehearsal, and contingency planning will organically combine these four components to achieve intelligent and automated management throughout the river network governance process. This will greatly enhance the efficiency of river network scheduling and control, reduce the human and material costs of river network management, and improve the level and capability of water management information systems.

2. Regional status

2.1. Regional overview

Kunshan is located in the central part of the Yangcheng-Dianmao area in the Taihu Basin, in the southeastern part of Jiangsu Province, between Shanghai and Suzhou. It is a county-level city under the administration of Suzhou. To the north and northeast, it borders the cities of Changshu and Taicang. To the east, it shares boundaries with the Jiading and Qingpu districts of Shanghai. To the west, it adjoins the Suzhou districts of Xiangcheng, Wuzhong, and the Suzhou Industrial Park. To the south, the ancient water town of Zhouzhuang Town borders the Wujiang District, with direct access to Zhejiang Province. The maximum straight-line distance from east to west is 33 km, and the distance from north to south is 48 km, with a total area of 931 km², of which the water area accounts for approximately 24%.

Kunshan has a subtropical monsoon climate typical of the southern part of East Asia. The winters are cold and dry, while the summers are hot and humid. The region experiences distinct seasons with abundant sunlight and ample rainfall. The average annual temperature is 17.6°C, the average annual precipitation is 1200.4 mm, and the average annual sunshine duration is 1789.2 hours. The air quality is excellent, meeting national Grade II standards for over 300 days each year. Kunshan is part of the Taihu Plain in the Yangtze River Delta. The area is characterized by a dense river network, flat terrain, and a slight inclination from southwest to northeast. The natural slope is minimal, with ground elevations mostly ranging from 2.8 to 3.7 meters (based on the Wusong Zero Point), with an average elevation of 3.4 meters.

Kunshan is a famous water town in southern China, with a dense network of rivers and an intricate system of lakes. There are more than 2,800 rivers and waterways in total, with a combined length exceeding 2,800 km.

2.2. Construction status

At present, Kunshan lacks relevant business systems such as flood control scheduling support models and emergency scheduling support systems. The existing information systems were established early, but due to incomplete infrastructure development, insufficient data completeness, and the development of related technologies, the current systems are unable to support flood prevention forecasting and scheduling applications. Kunshan is located in a plain river network area where the flow direction and velocity of water bodies during drainage and irrigation are complex. In daily management, such as flood scheduling, without professional models or predictive simulation technologies, it is difficult to comprehensively understand the water security status of the city’s main river network and the temporal and spatial trends of changes. Moreover, it is not possible to quickly simulate and demonstrate the effects of different scheduling plans.

3. Technology application approach based on the integrated four-preparation system

To address the insufficient integration of the existing Four-Preparation System, this study proposes the following technological application approach:

3.1. Building a unified data platform

3.1.1. Breaking data silos

Integrate rainfall forecast data from the meteorological department, water level and flow monitoring data from the hydrological department, water quality monitoring data from the environmental protection department, drainage network data from the urban construction department, etc., to build a comprehensive river network data resource pool. Achieve horizontal and vertical data sharing and business coordination [4].

3.1.2. Establishing data standards

Develop unified standards for data collection, transmission, storage, and processing, including the collection frequency, transmission protocols, storage formats, and processing methods for data such as water levels, flow, and water quality, ensuring data accuracy and comparability. Ensure data quality and consistency.

3.1.3. Developing data interfaces

Develop standardized data interfaces to facilitate data exchange and sharing between different systems. For example, develop Web Service or API-based data interfaces to enable data interoperability between meteorological, hydrological, environmental protection, urban construction, and other systems.

3.2. Establishing the integrated Four-Preparation system mechanism

3.2.1. Forecast-driven early warning

Use forecast results as inputs for early warning, establishing a linkage mechanism between forecasting and early warning, and achieving accurate release of early warning information. When the forecast model predicts that the rainfall in the next 24 hours will exceed 100 mm, it will automatically trigger a flood warning and send the warning information to relevant personnel and the public through SMS, WeChat, APP, etc.

3.2.2. Early warning triggers simulation

When the early warning level reaches a certain threshold, it automatically triggers the simulation system, simulating the river network's water conditions, water quality, and ecological changes under different scheduling scenarios, providing scientific support for plan formulation. When the flood warning level reaches orange, the flood simulation system will be automatically activated to simulate the flood evolution process under different flood release schemes, evaluating the inundation range, economic losses, and social impact of various scenarios.

3.2.3. Simulation supporting emergency plans

Based on the simulation results, optimize and adjust emergency plans to improve their relevance and operability. Based on flood simulation results, optimize and adjust flood release plans to determine the best release timing and volume, minimizing flood damage.

3.2.4. Feedback to forecasting from emergency plan

Provide real-time data such as rainfall, water levels, and flow from the execution of flood plans back to the forecasting model, used for model parameter calibration and validation, improving forecast accuracy. On this basis, the execution status of emergency plans is fed back to the forecasting system, continuously optimizing the forecasting model and enhancing its accuracy.

3.3. Developing the integrated Four-Preparation system platform

3.3.1. Integrating Four-Preparation functions

Develop a WebGIS-based integrated Four-Preparation System platform to visually display and interactively operate the functions of forecasting, early warning, simulation, and emergency plans. Integrate the four components of forecasting, early warning, simulation, and emergency plans into one platform to ensure seamless connection and coordinated operation of the four preparations.

3.3.2. Visual display

Use maps, graphics, tables, animations, and other methods to intuitively display the results of the four preparations, making it easier for decision-makers to quickly grasp the water conditions, water quality, and ecological status of the river network.

3.3.3. Intelligent analysis

Leverage big data, artificial intelligence, and other technologies to deeply mine and analyze four-preparation data, providing intelligent decision-making support for river network management.

3.4. Strengthening data sharing and business coordination

3.4.1. Establishing a data sharing mechanism

Clarify the data sharing responsibilities and obligations of each department, develop a data sharing directory and process, and ensure the standardization and institutionalization of data sharing. Formulate relevant management regulations to clarify the scope, methods, timeframes, and responsibilities of data sharing between departments.

3.4.2. Strengthening business coordination

Establish a cross-departmental coordination mechanism, clearly define the responsibilities and collaborative processes of each department, and form a unified effort in river network management.

4. Practical application system construction

4.1. Models

Based on the river network characteristics of the Kunshan area, basic data such as the terrain of the regional watershed, land use, river network, lakes, and sluice pump projects are collected to construct an integrated model for river network flow forecasting and scheduling. By collecting monitoring data to calibrate the model, the system designs business application scenarios such as river network forecasting, sluice pump scheduling, and regional water balance analysis. Through the WebSocket interface, the model service is provided to the business application layer, offering technical support for regional flood control and drainage forecasting, sluice pump operation scheduling, and flood prevention situation analysis.

In response to Kunshan’s flood prevention forecasting and scheduling business needs, combined with the regional river network’s flow movement characteristics, a modeling approach is designed that nests the Kunshan fine river network model into a regional backbone watershed model. A statistical correlation model is used to forecast upstream inflows to the region, and a fine river network, sluice pump projects, and flood prevention drainage models are used to calculate the rainfall-runoff in the region. A tidal level forecast model is applied to forecast tidal levels along the river for downstream river channels. Meanwhile, the model fully reflects the influence of river channels, tidal levels, and flood prevention drainage sluice pump scheduling by integrating the downstream backbone river network and flood control sluice pump models along the river. The following three main models are introduced:

4.1.1. Hydrological runoff generation model

Given Kunshan’s location in the lower plain river network area of the Taihu Basin and its urbanization characteristics, a distributed hydrological model needs to be established. The regional underlying surface is divided into four types: water surface, paddy fields, dry land, and construction land. Evaporation patterns of water bodies are established based on regional evaporation data, and a water surface runoff generation model is created. Based on the rice cultivation irrigation regime, a runoff generation model for paddy fields is developed. A new runoff generation model for the Xin’anjiang River is established to reflect the rainfall redistribution process for dry land after precipitation. Additionally, a runoff generation model for urban areas is built based on the evaporation pattern of construction land. Using system theory and functionality, GIS is utilized to manage the spatial topological relationships of various underlying surfaces, creating a fully digitalized, spatially topologically related distributed regional runoff module [6]. Since different underlying surfaces have different runoff generation patterns, the underlying surfaces within the scope of Kunshan’s water conservancy model are classified into four types: water surface, paddy fields, dry land, and urban roads (construction land), and modeling is performed for each type [5].

4.1.2. River network hydrodynamics model

Kunshan features a dense river network, with rivers crisscrossing and forming a ring-shaped network. The key rivers in the area, such as the Wusong River and Qipu River, form an interwoven layout and play a significant role in water exchange between rivers, lakes, and marshes. There are 107 important rivers in total. Based on cross-sectional data from the rivers, a hydrodynamic model for Kunshan’s river network is constructed to simulate the reciprocal movement of water flow and coupled with the hydrological forecasting model for the plain area. The runoff model for the plain slope is relatively complex. In addition to being influenced by the underlying surface and terrain, slope runoff is also related to the density of the conceptualized river network. The slope runoff in Kunshan is modeled using a distributed unit hydrograph model for the plain area. GIS maps are used to calculate the river network density, the river runoff length in hydrological sub-regions, the slope runoff velocity, and the probability of river channel grid cells being reached by runoff in different time periods. This information is then used to determine the distributed slope runoff unit hydrograph for the plain area. By incorporating the distributed unit hydrograph runoff results into the river network hydrodynamic model, water production models are coupled with hydrodynamic models at the river cross-sections [5].

4.1.3. Flood control scheduling model

Based on the hydrological and hydrodynamic models of the river network, real-time rainfall and water condition data, as well as scheduling requirements, are used to recommend scheduling schemes for water conservancy projects, achieving flood control and drainage scheduling objectives, and providing decision support for flood prevention command [6]. **A) Scheduling Scheme Recommendation:** Through the river network hydrological and hydrodynamic models, combined with the flood control and drainage standards and requirements of the Kunshan area, research is conducted on the scheduling schemes for sluice pump projects that meet regional flood control and drainage requirements under various rainfall, upstream inflow, and tide level conditions. A library of sluice pump project scheduling plans is established. Based on rainfall and operational conditions, watershed scenario identification is carried out, and the current scheduling scheme for the sluice pumps is formed by referencing the library of sluice pump scheduling plans. The preliminary scheduling scheme is then input into the river network hydrodynamic model for simulated adaptation calculations. Based on the scheduling objectives, adjustments to the sluice pump project are made to form a scheduling scheme that satisfies the current scenario, and scheduling scheme recommendations are provided to support Kunshan’s flood control scheduling decision-making process. **B) Forecast Rainfall Interaction:** The model provides an interactive interface for forecast rainfall, allowing the setup of different future rainfall scenarios. The river network hydrological and hydrodynamic models are used to forecast the water level and flow processes at key river cross-sections and the hydrological runoff processes in various zones under different rainfall conditions. **C) Forecast Storm Surge Flooding Interaction:** An interactive interface for tide levels is provided in the model, enabling the quick setup of different future storm surge flooding scenarios. Using the river network hydrological and hydrodynamic models, the forecast of water level and flow processes at key river cross-sections in the region is quickly and accurately conducted under the combined influence of astronomical tides and storm surge flooding. **D) Forecast Upstream Inflow Interaction:** The model provides an interface for upstream inflow interaction, enabling the quick setup of different upstream inflow scenarios. Using the river network hydrological and hydrodynamic models, the forecast of water level and flow processes at key river cross-sections in the region is quickly and accurately conducted under different upstream inflow conditions. **E) Sluice Pump Water Conservancy Engineering Scheduling Interaction:** Sluice pump project optimization scheduling is based on previous forecast results, considering both the optimization scheduling of individual water conservancy projects and the coordinated optimization of the water conservancy project group. The model provides an interactive interface for sluice pump project scheduling, allowing for the use of different sluice pump scheduling schemes, quick setup of scheduling rules, and the fast and accurate forecast of water level and flow processes at key river cross-sections in the region under different sluice pump scheduling scenarios using the river network hydrological and hydrodynamic models.

4.2. Business processes and overview

This research program, based on Kunshan’s smart water conservancy brain, conducts inflow and outflow forecasts for Kunshan, water level forecasts for representative stations and key embankment areas in Kunshan, following the “forecast-warning-preparation-plan” approach. This approach spans the entire design process of an integrated business application system for river, lake, and embankment multi-objective four-preparation, effectively supporting Kunshan’s water disaster defense operations. Additionally, based on Kunshan’s digital water management system, it upgrades and visualizes the reflection of Kunshan’s river network system’s water safety status, presenting content across 10 aspects: comprehensive monitoring, rainfall statistical analysis, water condition statistical analysis, operational condition statistical analysis, inflow and outflow analysis, rainfall isohyet map generation, river network flow state simulation, key water source situation, dry and tributary flow and water quality conditions, and video information [7].

4.3. Four-Preparation business system

(1) Forecast: Based on water conservancy model forecast results, analyze and display the future spatiotemporal hydrological variations and extreme hydrological values of Kunshan's river network system. The content includes four aspects: forecast model driving, forecast water level display, forecast water quality display, and water composition display.

(2) Warning: Based on forecast results, compare alarm indicators for representative stations (such as Ba Cheng, Kunshan, Chen Mu, and Zhou Xiang), guarantee water levels, and the elevation of levee sections along the Taihu River, to build a risk warning service.

(3) Preparation: Based on Kunshan's digital water management system, perform comparative analysis of the forecast results of different scheduling schemes, and dynamically simulate and analyze the future spatiotemporal variation processes under different scheduling scenarios.

(4) Plan: Based on the forecast, warning, and preparation results, as well as the optimized scheduling schemes, emergency flood control plans, water quantity and flood scheduling plans, and plans for exceeding flood levels are established. One-click generation of flood control plans is supported, and model forecast results are evaluated based on forecast accuracy at representative station water level and water quality.

(5) Forecast-Scheduling Integrated Service Platform: In addition to manual forecasting functions, there is also an automated forecast function triggered by scheduled water conservancy models, which automatically stores and visualizes forecast results, manages station information configuration, and tracks forecast task execution, improving forecast efficiency. Digital processing of plan documents and engineering scheduling schemes is performed, with scheduling scheme execution, warning monitoring, and status display in a unified view to alert anomalies. Furthermore, a backend configuration function is developed for management purposes.

5. Conclusion

This study, through the construction of the Kunshan River Network Multi-Objective Coordination Four-Preparation Integrated System, comprehensively organizes the rainwater monitoring and perception system, consolidates the data foundation, builds the model platform, improves the business platform, and forms the Kunshan River Network Multi-Objective Coordination Four-Preparation Integrated System. This system addresses the problem that existing systems cannot support flood forecasting and scheduling applications and fills the gap in professional model forecasting and prediction technologies. It also provides a comprehensive understanding of the water conditions and trends of the key river network. The Kunshan River Network Multi-Objective Coordination Four-Preparation Integrated System plays a core role in managing data and model resources for lower-level operations and supporting business applications for higher-level operations, while also providing information-sharing services. These two functions can be described as the integration and sharing of underlying data resources and the integration of upper-level application software resources. The system provides fundamental services and general application functions for various application systems, aiming to achieve high reuse of software components and ensuring the high availability, flexibility, scalability, security, stability, and other performance metrics of the entire application system.

References

[1] Deltares. (2023). DELFT3D. Retrieved from https://www.deltares.nl/en/software/delft3d/

[2] US EPA. (2023). BASINS. Retrieved from https://www.epa.gov/ceam/basins

[3] Thielen, J., Bartholmes, J., Ramos, M. H., & de Roo, A. (2009). The European Flood Alert System – Part 1: Concept and development. *Hydrology and Earth System Sciences, 13*(2), 125-140.

[4] Fan, Z., Liu, G., & Yang, G. (2022). Construction and application of the intelligent scheduling system for urban flood control "Four Previsions". *Jiangsu Water Resources, (12)*, 5-10.

[5] Chen, F. (2020). Study and application of the hydrological and hydraulic model of river networks in the Wenhuang Plain area of Taizhou. *Engineering Technology Research, 5*(22), 217-218.

[6] Su, C. (2021). Research and design of the "smart water conservancy" information model in Zhenjiang. *Water Conservancy Technology Supervision, (03)*, 33-36.

[7] Liu, Y., Liu, C., & Hao, M. (2022). Construction of the digital twin basin data foundation for flood control "Four Previsions". *China Flood and Drought Prevention, 32*(6), 6-4.