ГИДРОТЕХНИЧЕСКОЕ СТРОИТЕЛЬСТВО, ГИДРАВЛИКА И ИНЖЕНЕРНАЯ ГИДРОЛОГИЯ/HYDRAULIC ENGINEERING, HYDRAULICS AND ENGINEERING HYDROLOGY

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MODERNIZING HYDROLOGICAL FORECASTING IN THE YANGTZE RIVER BASIN: FROM EXPERIENCE TO INTELLIGENCE

Research article

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Abstract

The modernization of hydrological forecasting in the Yangtze River Basin represents a comprehensive response to climate change, integrated water governance, and national security needs. This paper reviews major achievements in constructing a basin-wide monitoring network and a prototype digital twin platform, forming a new framework that links atmosphere, land, water, and infrastructure. Through the integration of multiscale seamless precipitation coupling forecasts, distributed hydrological simulations, forward–inverse coupled reservoir scheduling, multisource probabilistic forecasting, and intelligent evolutionary correction, forecasting accuracy has markedly improved. Practical applications during the 2020 flood and the 2022 drought demonstrated substantial socio-economic benefits — preventing the activation of the Jingjiang Flood Diversion Area and protecting over 13 million people from water scarcity. The study identifies four strategic directions for future progress: AI-driven forecasting, diversified element integration, refined distributed modeling, and smart system architecture optimization. It argues that hybrid mechanism — data modeling and digital twin technologies — will be pivotal for realizing intelligent, anticipatory basin governance. The modernization experience of the Yangtze River Basin thus offers a globally applicable "Yangtze Model" for intelligent management of mega river systems.

Keywords: Yangtze River Basin, hydrological forecasting, digital twin, flood and drought management, artificial intelligence.

МОДЕРНИЗАЦИЯ ГИДРОЛОГИЧЕСКОГО ПРОГНОЗИРОВАНИЯ В БАССЕЙНЕ РЕКИ ЯНЦЗЫ: ОТ ОПЫТА К ИНТЕЛЛЕКТУ

Научная статья

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Аннотация

Модернизация гидрологического прогнозирования в бассейне реки Янцзы представляет собой комплексный ответ на изменение климата, комплексное управление водными ресурсами и потребности национальной безопасности. В данной статье рассматриваются основные достижения в создании сети мониторинга всего бассейна и прототипа платформы цифровых двойников, формирующей новую структуру, связывающую атмосферу, сушу, водные ресурсы и инфраструктуру. Благодаря интеграции многомасштабных бесшовных прогнозов осадков, распределенного гидрологического моделирования, прямого и обратного сопряжения планирования водохранилищ, вероятностного прогнозирования с использованием нескольких источников и интеллектуальной эволюционной коррекции, точность прогнозов значительно повысилась. Практическое применение во время наводнения 2020 года и засухи 2022 года продемонстрировало существенные социально-экономические преимущества, предотвратив активизацию зоны отвода паводков Цзинцзян и защитив более 13 миллионов человек от дефицита воды. В исследовании определены четыре стратегических направления будущего прогресса: прогнозирование на основе искусственного интеллекта, диверсифицированная интеграция элементов, усовершенствованное распределенное моделирование и оптимизация архитектуры интеллектуальных систем. В статье утверждается, что гибридные механизмы моделирования данных и технологии цифровых двойников будут играть ключевую роль в реализации интеллектуального, опережающего управления бассейном. Таким образом, опыт модернизации бассейна реки Янцзы предлагает глобально применимую «модель Янцзы» для интеллектуального управления мегаречными системами.

Ключевые слова: Бассейн реки Янцзы, гидрологическое прогнозирование, цифровой двойник, борьба с наводнениями и засухами, искусственный интеллект.

Introduction

As the core region of China's socioeconomic development, the Yangtze River Basin covers one fifth of the nation's territory yet supports over one third of its population and economic output [1]. Facing the world's largest water resources engineering system — comprising cascade reservoirs, interbasin water diversion projects, and flood detention areas—precise and timely hydrological forecasting is a crucial foundation for the scientific operation of hydraulic projects. However, as the largest river basin in China, the Yangtze River faces both natural and anthropogenic challenges in hydrological forecasting. The basin's complex topography spanning three geomorphological steps, spatially and temporally uneven monsoonal precipitation, and intensifying human activities all contribute to making accurate hydrological forecasting a highly complex and challenging task [2], [3], [4].

This paper analyzes and summarizes the Yangtze River Basin's practical experience in building an integrated monitoring network and a prototype digital twin platform, outlines key technological innovations that have driven forecasting from empirical approaches toward intelligent systems, and reviews the major advances in monitoring, digital platforms, and core technologies, as well as the significant benefits achieved in flood and drought management.

The practice of Yangtze River hydrological forecasting in improving the accuracy of flood operation forecasting

After years of technical iteration and operational practice, the accuracy of rainfall and runoff forecasting across the Yangtze River Basin has greatly improved. According to the Hydrology Bureau's rainfall forecast scoring system, during the flood season, the average score for 72 hour areal rainfall forecasts exceeds 88, and the accuracy of medium term forecasts (4–10 days) exceeds 80 — both surpassing standard product requirements [5], [6].

For the Three Gorges Reservoir, short term (1–3 d) inflow forecasts maintain a mean relative error below 10%, while medium term (4–10 d) forecasts have errors ranging from 8% to 22,7%. Monthly inflow trend forecasts achieve an accuracy of 73%. For the middle and lower reaches of the Yangtze, water level forecasts within 72 hours have an average deviation of less than 0.20 m between Chenglingji and Datong stations, and key floods can be accurately predicted 3–5 days in advance. Long term forecasts can effectively identify flood–drought trends during the main flood season and refine spatial drought–flood distributions through monthly and autumnal projections.

Overall, current hydrometeorological forecasts in the basin can accurately capture heavy rainfall events, flood peaks, timing, and volume, providing strong support for the scientific operation of hydraulic projects [7], [8].

The practice of Yangtze River hydrological forecasting in flood and dry season forecasting

3.1. The 2020 Basinwide Flood

In 2020, the Yangtze River Basin experienced a major flood event. In mid-August, heavy inflows occurred in the Min–Tuo and Jialing Rivers, producing the largest flood since the impoundment of the Three Gorges Reservoir, with a peak inflow of 78,000 m³/s (08:00, August 20). The short to medium term forecasts accurately predicted, one week in advance, heavy rainfall exceeding 250 mm across the Min–Tuo and Jialing River basins and forecasted a compound flood exceeding 60,000 m³/s entering the reservoir. Subsequent rolling updates yielded a final forecast that matched observed inflows with high precision.

Based on these forecasts, upstream reservoirs were jointly and precisely operated, intercepting 19 billion m³ of floodwater. Analysis shows that the flood peak at Cuntan Station, originally a 90-year recurrence event (130 year in flood volume), was reduced to a 20 year (40 year) level, significantly alleviating downstream flood pressure and avoiding the activation of the Jingjiang Flood Diversion Area —preventing economic losses exceeding 10 billion RMB [9].

3.2. The 2022 Drought Forecast and Response

During the 2022 flood season, the Yangtze River Basin suffered the most severe meteorological and hydrological drought since 1961, with record low water levels in the middle and lower reaches. The Hydrology Bureau accurately predicted potential drought conditions in early warnings issued before the flood season and reaffirmed severe drought risks in July, followed by timely low water alerts. Between July and October, nearly 600 forecast bulletins and analytical reports were released, covering hydrological conditions, short and medium term rainfall forecasts, and drought situation assessments.

For Hankou Station, the water level was forecasted to drop below 13,30 m five days in advance and below 12,80 m two days in advance; for Datong Station, discharges below 10,000 m³/s were predicted six days in advance.

Based on these forecasts, two "Joint Drought Relief and Water Supply Operations" and one "AntiSalt Intrusion Water Supply Operation" were implemented across the upper and middle basins. These measures improved water intake conditions along the middle and lower main stem, the two lakes region, and the Yangtze estuary, benefiting 13,85 million rural residents. The operations ensured irrigation water for 4,316 million hectares of autumn crops across 356 major irrigation zones. An additional 50,1 million m³ of water was supplied to the estuary, while upstream reservoir storage reached 49,59 billion m³ by the end of the flood season—safeguarding food and water security [10].

Prospects for the Modernization of Hydrological Forecasting

The modernization of hydrological forecasting in the Yangtze River Basin is essential for climate adaptation, integrated water governance, and efficient water resource utilization. Future progress can be made across four major dimensions: artificial intelligence, diversified forecast elements, refined distributed modeling, and system architecture optimization.

1) Artificial Intelligence Redefining Hydrological Cognition.

AI-driven forecasting models will be at the core of future progress. Reinforcement learning can optimize multiobjective scheduling decisions, while computer vision can extract information from satellite imagery. The construction of basin scale knowledge graphs linking historical disaster cases with real-time monitoring data will enable intelligent diagnosis, warning, and automated emergency response recommendations.

2) Diversification and Deep Integration of Forecast Elements.

Modern hydrological forecasting must transcend traditional flow and stage monitoring frameworks. Integration of satellite-based precipitation retrieval, IoT-based soil moisture sensing, UAV-based terrain mapping, and reservoir operation data will establish multidimensional coupling among hydrological, meteorological, salinity, and drought variables. Such diversification enhances scientific coordination of hydraulic operations under extreme conditions and provides a full element decision foundation for flood defense, water environment protection, and ecological restoration.

3) Enhancing Refinement of Distributed Hydrological Simulation.

Building on the complexity and systemic nature of the basin, remote sensing, IoT, and ground-based observation data should be integrated to form a high-resolution (L3level) all element digital foundation. Developing kilometer scale digital mirrors of the basin enables distributed hydrological simulation that accounts for both hydraulic regulation and urbanization impacts. This refined modeling framework supports precise simulation of full basin water cycle processes and deepens the application of distributed models in flood and drought early warning.

4) Modernizing Forecast Systems to Support Smart Governance.

The construction of forecasting systems should aim to establish three defensive lines supporting four integrated functions — forecasting, early warning, rehearsal, and planning. This comprehensive framework will form a full chain technology system linking “atmosphere–precipitation–runoff–infrastructure”. Consistent with the goals of the Digital Twin Basin, a new model integrating physical and digital systems should be continuously advanced. By leveraging the rapid iteration and low-cost testing advantages of digital twin platforms, and through the deep fusion of data, algorithms, and computing power, virtual simulations and optimization of flood scheduling schemes can be realized — enhancing flood control and disaster reduction across the basin.

The modernization of hydrological forecasting in the Yangtze River Basin should thus follow a “one–two–three–four” strategic pathway: guided by a structured framework (“one”), driven by artificial intelligence (“two”), powered by refinement and diversification (“three”), and integrated within digitalized information systems (“four”) — achieving a transition from water management (Zhishui) tosmart water governance (Zhishui), and providing a solid foundation for the high quality development of the Yangtze River Economic Belt.

Conclusion

The modernization of hydrological forecasting in the Yangtze River Basin is not only a strategic response to climate change and a cornerstone of integrated basin management but also a vital component of national security and disaster resilience. The Yangtze River Basin has developed an integrated “atmosphere–land–water–infrastructure” monitoring network and a digital twin platform, facilitating the transformation of forecasting from empirical to intelligent systems.

At the technical core, the development of multiscale seamless precipitation coupling forecasts, distributed hydrological simulation, forward–inverse coupled reservoir scheduling, multisource probabilistic flood forecasting, intelligent evolutionary correction, and full cycle real-time scheduling has significantly enhanced forecasting accuracy.

In practical application, the 2020 flood forecasts successfully prevented the activation of the Jingjiang Flood Diversion Area, reducing flood losses by more than 10 billion RMB. The 2022 drought response scheduling benefited 13,85 million people, safeguarding food and water security.

Nevertheless, challenges remain — particularly the impacts of climate change on hydrological processes, the nonlinear influence of reservoir systems, and conflicts in multiobjective decision-making. Future progress should focus on integrating digital twin technologies and AI, overcoming multiscale model coupling bottlenecks, and establishing a new hybrid paradigm that merges physical and digital domains. The experience of the Yangtze River Basin can thus provide a “Yangtze Model” for intelligent governance of mega river basins worldwide.

Конфликт интересов

Не указан.

Рецензия

Все статьи проходят рецензирование. Но рецензент или автор статьи предпочли не публиковать рецензию к этой статье в открытом доступе. Рецензия может быть предоставлена компетентным органам по запросу.

Conflict of Interest

None declared.

Review

All articles are peer-reviewed. But the reviewer or the author of the article chose not to publish a review of this article in the public domain. The review can be provided to the competent authorities upon request.

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