Postprint on Hydro-ecological Regulation in the Yangtze River Basin and Development of the Yangtze River Simulator

Authors: Xia Jun, Lin Zhonghui, Zhan Chesheng, Gao Wenjuan, Li Yunliang, Yao Jing, Zeng Sidong, Huang Renyong, Wang Hongzhu

Date: 2024-03-27T00:00:00+00:00

Abstract

Ecological protection and green development in the Yangtze River Basin constitute important components of building a Beautiful China. This paper first reviews the main ecological challenges facing the upper, middle, and lower reaches of the Yangtze River Basin and its typical river-connected lakes, and analyzes the achievements and shortcomings of existing water ecological scheduling practices in the basin. Secondly, it summarizes the research and development progress of the Yangtze River Simulator over the past five years, along with its preliminary design for ecological scheduling of the main river channel and river-connected lakes. Through coupled hydrological-hydrodynamic-ecological simulation practices for the main river channel and river-connected lakes conducted via the Yangtze River Simulator, preliminary optimization schemes for the ecological scheduling of the Three Gorges Reservoir that meet the water ecological requirements of typical reaches in the main stream have been obtained. Finally, it proposes recommendations for the direction of water ecological scheduling in the Yangtze River Basin and for the further development of the Yangtze River Simulator.

Full Text

Ecological Operation in the Yangtze River Basin and Development of the Yangtze River Simulator

Citation Format: Xia J, Lin Z H, Zhan C S, et al. Ecological operation in Yangtze River basin with Yangtze River Simulator. *Bulletin of Chinese Academy of Sciences*, 2023, 38(12): 1767-1780, doi: 10.16418/j.issn.1000-3045.20230927001.

Xia J, Lin Z H, Zhan C S, et al. Ecological operation in Yangtze River basin with Yangtze River Simulator. *Bulletin of Chinese Academy of Sciences*, 2023, 38(12): 1767-1780, doi: 10.16418/j.issn.1000-3045.20230927001. (in Chinese)

Authors: XIA Jun[1,2], LIN Zhonghui[2*], ZHAN Chesheng[2], GAO Wenjuan[3], LI Yunliang[4], YAO Jing[4], ZENG Sidong[5], HUANG Renyong[6], WANG Hongzhu[3]

[1] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China; [2] CAS Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; [3] State Key Laboratory of Fresh Water Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China; [4] Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences, Nanjing 210008, China; [5] Chongqing Institute of Green and Intelligent Technology, Chinese Academy of Sciences, Chongqing 400714, China; [6] Changjiang River Scientific Research Institute, Wuhan 430010, China

Abstract

Ecological protection and green development in the Yangtze River basin are critical components of building a Beautiful China. This paper first reviews the main ecological challenges facing the upper, middle, and lower reaches of the Yangtze River and its typical river-connected lakes, and analyzes the achievements and shortcomings of existing water ecological operation practices in the basin. Second, it outlines the research and development progress of the Yangtze River Simulator over the past five years and its preliminary design for ecological operation of the main river channel and river-connected lakes. Through coupled hydrological-hydrodynamic-ecological simulation practices for the main river channel and river-connected lakes using the Yangtze River Simulator, an optimized ecological operation scheme for the Three Gorges Reservoir was developed to meet the water ecological requirements of typical river reaches. Finally, recommendations are proposed for the future direction of water ecological operation in the Yangtze River basin and further development of the Yangtze River Simulator.

Keywords: Yangtze River basin, Yangtze River Simulator, water ecology, ecological operation

Since the 18th National Congress of the Communist Party of China, ecological civilization construction has been prioritized. In March 2018, the First Session of the 13th National People' s Congress adopted a constitutional amendment that enshrined new development concepts, ecological civilization, and the goal of building a Beautiful China in the Constitution, establishing the constitutional status of ecological civilization. Building an ecological civilization system, improving coordination mechanisms in the ecological civilization domain, and promoting comprehensive green transformation of economic and social development are important tasks for national development during the 14th Five-Year Plan period.

In 2014, the development of the Yangtze River Economic Belt became a major national strategy for the new era. In 2016, 2018, 2020, and 2023, President Xi Jinping presided over symposiums in Chongqing, Wuhan, Nanjing, and Nanchang to promote green development of the Yangtze River Economic Belt, establishing the overarching principle of "jointly protecting the Yangtze River without large-scale development" and "ecological priority, green development," highlighting the strategic importance of high-quality green development of the Yangtze River Economic Belt in national ecological civilization construction. Since 2019, the Ministry of Ecology and Environment and the National Development and Reform Commission have jointly implemented the Yangtze River protection and restoration campaign, resulting in significant improvements in water environmental quality and initial containment of water ecological degradation. However, problems such as inadequate non-point source pollution control, shrinking lake wetlands, and biodiversity loss remain prominent. Under the combined influence of climate change and human activities, the future ecological protection situation in the Yangtze River basin remains severe and complex, with water environment governance and water ecological restoration tasks still facing enormous challenges. On March 1, 2021, the *Yangtze River Protection Law of the People' s Republic of China* officially came into effect. Implementing the *Yangtze River Protection Law* and achieving high-quality green development under ecological priority through scientific and unified basin system governance requires urgent progress on two important tasks: establishing a national-level, whole-basin coordination mechanism and strengthening the leading role of scientific and technological innovation to support the construction of a basin water system simulation and regulation device for ecological environment restoration, protection, and integrated management.

In early 2019, the Chinese Academy of Sciences launched the Strategic Priority Research Program (Category A) "Beautiful China Ecological Civilization Science and Technology Construction Project." Project 4, "Integrated Management and Application of Water Environment and Water Ecology in the Main Stream of the Yangtze River Economic Belt," focuses on urgent water ecological and water environmental issues for high-quality green development in the Yangtze River Economic Belt, with water as the bond. The research team first proposed the concept of the "Yangtze River Simulator," which develops a comprehensive basin water system simulation system based on integrated space-air-ground monitoring of basin information to provide comprehensive technical solutions for basin water system regulation and integrated management [7,8]. This paper mainly analyzes water ecological problems in the Yangtze River basin, introduces the research and simulation practices of the Yangtze River Simulator in basin water ecological operation, and aims to provide references for water ecological operation management in the Yangtze River basin.

In response to global ecological and environmental problems, scholars worldwide have proposed and developed a series of Earth System Models (ESMs). Based on global atmospheric dynamic models coupled with ocean, land, and cryosphere dynamic models, these aim to predict, reconstruct, and deeply understand global climate change processes and assess climate change impacts on ecology and the environment. In March 2002, Japan built the Earth Simulator (ES) [1], which has now evolved to the ES4 version. In 2012, the NOAA Geophysical Fluid Dynamics Laboratory in the United States developed the Earth System Model (ESMs) [2]. In 2018, the U.S. Department of Energy led the release of the Exascale Energy Earth System Model (E3SM) [3], which, in addition to climate change prediction, assesses climate change pressure on energy infrastructure. In 2020, the Swiss Federal Institute of Technology developed a Modular Earth System Model (MESMER) [4]. In 2010, Zeng Qingcun et al. [5] proposed developing China' s Earth System Dynamic Model in response to international trends in Earth System dynamic model research. In October 2022, the Institute of Atmospheric Physics of the Chinese Academy of Sciences, in collaboration with Tsinghua University, officially completed the "Earth System Numerical Simulation Facility," which is significant for deeply understanding climate change impacts on global and China' s regional environment. In 2021, Yu Guirui et al. [6] proposed building a "Terrestrial Ecosystem Numerical Simulator" to develop a continental-scale terrestrial ecosystem simulation and analysis device integrating "multi-source data analysis-ecological process simulation-spatiotemporal pattern assessment-ecological prediction and early warning" as a major infrastructure of China' s National Ecosystem Observation and Research Network. However, existing Earth System simulators focus on depicting the entire Earth system with relatively coarse spatial resolution. For example, the highest spatial resolution of the "Earth System Numerical Simulation Facility" is currently 5 km, which cannot finely characterize ground eco-hydrological processes or the impacts of human activities and management measures on basin eco-hydrological processes—processes whose fine simulation is essential for assessment, early warning, and regulation of basin water environment and water ecology.

The Yangtze River system provides critically important ecological services and constitutes vital support for the sustainable development of the Chinese nation [9]. The Yangtze River basin has high aquatic biodiversity, with over 400 fish species (348 freshwater species, 166 endemic), 145 amphibian species (49 endemic), 296 mollusk species (197 endemic), and 298 aquatic vascular plant species, forming an important germplasm resource bank that supports over 70% of the country' s freshwater fish production—40% of the world' s total. Under the combined influence of intense human activities and climate change, the Yangtze River basin is facing problems including regional water shortages, severe water pollution, and damaged water ecology in some areas, which have become important factors constraining regional sustainable development. More than 50,000 reservoirs with a total storage capacity accounting for 37% of the basin' s total surface runoff have greatly altered the water cycle characteristics and aquatic organism habitat environment in the Yangtze River basin.

The main water ecological problems in the Yangtze River basin are prominently manifested as declining aquatic biodiversity. Currently, rare species such as the Yangtze River dolphin and Chinese paddlefish are essentially extinct in the Yangtze River basin. Approximately 30% of fish species, as well as birds and shellfish, are endangered. The egg and larvae quantities of Chinese sturgeon, Dabry’ s sturgeon, Chinese sucker, and the four major Chinese carp species have significantly decreased. River-lake fishing yields have declined by nearly 80% over the past 50 years. The finless porpoise population has decreased by 80% over the past 20 years, with only 1,249 individuals remaining. Water ecological problems in the Yangtze River basin manifest differently in the upper, middle, and lower reaches, summarized as four main issues.

1.1 Water Ecological Problems Caused by Upstream Cascade Reservoir Groups

The upper Yangtze River basin is rich in hydropower resources. Cascade reservoir groups in the lower Jinsha River and Yalong River basins have been completed, providing stable energy support for national economic and social development. However, cascade reservoir group construction has significantly altered aquatic organism habitats, with two prominent problems:

(1) Persistent total dissolved gas (TDG) supersaturation impacts on fish. High dam operation makes TDG supersaturation a serious water environmental problem. In 2014, TDG supersaturated water flow downstream of the Xiluodu Dam lasting over a week caused 100,000 kg of fish deaths in the downstream Xiangjiaba reservoir area. Joint operation of cascade reservoir groups can lead to longer duration and higher cumulative effects of TDG supersaturation. Using hydrodynamic models to simulate and predict TDG supersaturation occurrence and distribution and optimizing hydropower generation modes and operation scheduling are currently the optimal approaches to address TDG supersaturation problems from high dam discharge in cascade reservoir groups [10].

(2) Persistent adverse effects of cascade reservoir groups on fish biodiversity. Cascade reservoir group construction has significantly altered upstream river hydrological regimes (including reduced flow velocity and changed water temperature stratification), blocked fish migration routes, and caused fish habitat fragmentation, leading to significantly reduced fish diversity. After the operation of the Xiluodu and Xiangjiaba power stations, fish species in the Suijiang section decreased from 54 to 35 [11]. A 2018 survey in the Yibin section of the National Nature Reserve for Rare and Endemic Fishes in the upper Yangtze River showed that among the original 36 spawning grounds, 61% had partially or severely degraded functions [12]. Comprehensive measures including building fish passage facilities, establishing protected areas and artificial spawning grounds, reservoir ecological operation, and habitat substitution will be the best approach to combine green hydropower development with fish protection.

1.2 Water Ecological Problems in the Three Gorges Reservoir Area

Due to flood control and power generation needs, the Three Gorges Reservoir experiences intense and frequent water level regulation, creating a series of water environment and water ecological problems mainly manifested in three aspects: reservoir drawdown zone, tributary backwater area, and the reservoir itself.

(1) Soil erosion and vegetation degradation in the reservoir drawdown zone. The drawdown zone has a water level fluctuation of up to 30 m, long inundation duration, and frequent out-of-season water level fluctuations, leading to large-scale degradation of original vegetation and serious soil erosion problems. In recent years, through ecological restoration and engineering management measures, the health of the drawdown zone ecosystem has shown a yearly stable and improving trend in most areas, but management of drawdown zones at the reservoir head and tail still requires attention.

(2) Algal bloom problems in tributary backwater areas. After impoundment of the Three Gorges Project, algal blooms appeared in tributary backwater areas due to nutrient input and altered hydrological regimes. The Three Gorges Reservoir has used tidal ecological operation to effectively suppress algal blooms in bay areas by altering hydrodynamic and habitat conditions. However, algal bloom prediction and early warning, and nutrient control in tributary water bodies, remain ongoing challenges.

(3) Declining fish biodiversity in the reservoir area. After impoundment, some original spawning grounds were submerged, and fish resources in the reservoir area have continuously decreased. According to surveys, fish species in the main reservoir channel decreased from 140-200 in the 1980s to 84 in 2013-2015 [13]. The causes and recovery mechanisms of fish resource decline and restoration require further in-depth research.

1.3 Water Ecological Problems in the Middle and Lower Reaches

The water ecosystem in the middle and lower reaches is deeply affected by water conservancy projects, river-lake sand mining, and land reclamation, with three prominent water ecological problems:

(1) Altered river-lake hydrological regimes and adverse impacts on aquatic ecosystems. Reservoir regulation and resulting riverbed incision have changed hydrological rhythms in the main stream and river-connected lakes, significantly impacting aquatic ecosystems. After Three Gorges Reservoir operation, annual runoff downstream decreased by 6%-10%, and annual sediment transport decreased by 63%-80%. The fine sediment released caused downstream riverbed scouring, with flood season water levels at the Datong section dropping 0.1-1 m under the same discharge. Significantly altered hydrological regimes and water temperature systems have destroyed growth conditions for aquatic plants and fish migration and spawning conditions, and reduced water self-purification capacity. Rapid

spring water level rise in the main stream downstream of the Three Gorges Reservoir affects the germination of hygrophytic and emergent plants, leading to significant changes in waterbird and fish habitats and affecting animal resources. Levee projects, river cutoff projects, branch-blocking projects, and beach tree-planting projects in the middle reaches have channelized the river, reducing aquatic organism habitat area, decreasing habitat heterogeneity, and lowering aquatic biodiversity [13].

(2) Lake reclamation has destroyed aquatic ecosystem integrity. Continuous lake reclamation, sedimentation, and lakeside construction have caused shrinking lake wetland area, degraded lakeside zone functions, and declining aquatic and riparian vegetation, reducing the lakeside zone' s capacity to intercept pollutants and reduce internal pollution sources, thereby destroying lake ecosystem integrity.

(3) River-lake sand mining and waterway regulation have destroyed aquatic organism habitats. Sand mining and waterway regulation have significantly altered river-lake geomorphology and hydrological processes, destroyed benthic habitats, and severely impacted benthic animals and aquatic plants. Increased suspended sediment concentration from sand mining reduces water transparency, significantly affecting plankton and aquatic plants.

1.4 Water Ecological Problems in Typical River-Connected Lakes

Historically, shallow lakes in the middle and lower Yangtze River were connected to the main stream, forming a river-lake compound ecosystem that became a world-rare freshwater species resource bank. However, since the 1950s, dam and gate construction in river-lake connections has severely affected lateral hydrological connectivity, leaving only Dongting Lake and Poyang Lake in river-connected status. Currently, Dongting Lake and Poyang Lake are affected by water conservancy project regulation, lake reclamation, and other human development activities, resulting in four serious water ecological problems:

(1) High algal bloom risk in local lake areas. Large-scale cyanobacteria aggregations have been observed in Duchang, Junshan Lake, Kangshan Lake, Cuoji Lake, and Zhanbei Lake in Poyang Lake. The eastern lake bay, with relatively slow water flow and higher total phosphorus and nitrogen concentrations, has experienced multiple algal bloom aggregations. East Dongting Lake also faces high algal bloom risk due to slow water flow.

(2) Significant reduction in submerged vegetation. Due to water surface shrinkage, habitats in some areas of river-connected lakes have shifted from aquatic to terrestrial succession, with submerged vegetation area greatly reduced and community structure simplified and diversity decreased [14].

(3) Declining benthic animal diversity and integrity. The dominant benthic

animal species in Poyang Lake have gradually shifted from large mollusks to small mollusks and insects, with obvious diversity decline [15]; while benthic animal integrity in Dongting Lake has also shown a significant downward trend [16].

(4) Threats to fish and finless porpoises under drought stress. After the complete fishing ban, fishing pressure decreased, fish resources increased, and finless porpoise numbers also showed an upward trend. However, affected by frequent low water levels and rapid drought-flood transitions in recent years, water recession rates in river-connected lakes have accelerated and water levels have dropped sharply, causing some finless porpoises and fish that could not retreat in time to be stranded in low-lying water bodies and die from drying.

2. Main Practices and Problems of Water Ecological Operation in the Yangtze River Basin

Since impoundment of the Three Gorges Reservoir, researchers have focused on ecological operation issues. Cheng Genwei et al. [17] proposed ecological operation objectives including maintaining river flood rhythms, preserving upstream-downstream sediment transport balance, promoting reservoir water exchange, and implementing flood control compensation regulation. Guo Wenxian et al. [18] quantitatively analyzed flow requirements for downstream river environment, hydrological-hydrodynamic needs during Chinese sturgeon spawning periods, and requirements during the four major Chinese carp spawning period, discussing Three Gorges Reservoir ecological operation objectives. From 2011-2020, the Changjiang Water Resources Commission conducted 14 ecological operation experiments in the Three Gorges Reservoir to promote natural reproduction of the four major Chinese carp in downstream river sections. Except for 2016 and 2020 when no large-scale reproduction occurred during ecological operation periods, implementation in other years played a positive role in promoting reproduction of fish producing drifting eggs [19]. From 2020-2021, the Hanjiang Water Resources and Hydropower Group conducted three ecological operation experiments in the Danjiangkou-Wangfuzhou section [20], targeting excessive growth of submerged plants such as *Elodea*. While ensuring water transfer volumes, they increased discharge flow to disturb submerged vegetation growth, effectively suppressing aquatic weed proliferation in the Wangfuzhou reservoir area.

Current ecological operation practices in the Three Gorges Reservoir still have relatively single objectives, considering only spawning needs of the four major Chinese carp. In reality, fish resource recovery also requires sufficiently large fattening waters rich in food organisms. Newly hatched fry must reach slow-flow or still-water environments rich in zooplankton; otherwise, survival rates from fry to juvenile fish (10-20 cm) can differ by thousands of times. Juvenile, sub-adult, and adult fish feeding on plankton, benthic animals, or aquatic plants have similar hydrological needs as their food organisms, also requiring low-flow-velocity environments. Therefore, future basin ecological operation should also consider hydrological process requirements that meet the entire life history processes of most fish species and their required food organisms (mainly floodplain plants).

3. Development of the Yangtze River Simulator and Design for River Channel Ecological Operation

3.1 Development of the Yangtze River Simulator

The Yangtze River Simulator is a basin simulation system and scientific device that takes the Yangtze River basin as its object and uses the basin water cycle as its bond to couple natural processes with human processes. The Yangtze River Simulator emphasizes interconnections and interactions among the upper, middle, and lower reaches of the Yangtze River and among lakes/reservoirs-shorelines-urban agglomerations. It emphasizes joint operation combining flood control, power generation, and aquatic organism protection, with the goals of "understanding the past Yangtze River, recognizing the present Yangtze River, and looking forward to the future Yangtze River," and integrates functions of "monitoring-simulation-assessment-warning-decision-regulation." After nearly five years of exploration, the systematic framework for Yangtze River Simulator construction has been basically formed (Figure 1 [Figure 1: see original paper]), and from the perspectives of perception systems, simulation systems, and service systems, the first-generation device of the Yangtze River Simulator has been developed.

In terms of perception system development, an integrated space-air-ground monitoring and surveillance system for the basin has been initially formed. A contact-type underwater in-situ water quality detection system based on continuous fine absorption spectra and a reflection-based hyperspectral imaging space-ground water quality detection system have been developed, currently achieving real-time online continuous high-frequency observation of water quality indicators at the Xiangxi River station in the Three Gorges Reservoir area and the Poyang Lake area. Using remote sensing interpretation, long-term water quality spatiotemporal variation data for Poyang Lake, Dongting Lake, Taihu Lake, and Hong Lake from 1987-2021 have been obtained, as have data on black and odorous water bodies in typical cities such as Wuhan, Chongqing, Shanghai, and Changsha. Monthly-scale interpretation products for water quality in the Yangtze River main stream and spatiotemporal variation data of the Yangtze River main stream shoreline over the past 40 years have been produced. A data sharing cooperation mechanism has been preliminarily established with environmental monitoring departments to jointly build a Yangtze River basin water ecology and water environment monitoring information platform.

In terms of model system development, a comprehensive Yangtze River main stream water system simulation and regulation platform has been constructed. Specialized models have been developed including a basin distributed eco-hydrological simulation model, basin non-point source pollution simulation model, Three Gorges Reservoir hydrodynamic-water quality-operation coupling model, Yangtze River middle and lower reaches main stream hydrodynamic-water quality coupling model, Poyang Lake and Dongting Lake two-dimensional hydrodynamic models, Yangtze River main stream typical reach water ecological simulation model, and Yangtze River main stream typical urban water system model. The accuracy of coupled simulation of specialized models has been verified [8]. At six key sections (Qingxichang, Wanxian, Chenglingji, Hankou, Hukou, and Datong), the Nash efficiency coefficients for flow and water level simulation reached satisfactory levels.

Based on the development of specialized models, the Yangtze River Simulator software platform has been developed, including a professional version and a decision-making version (Figure 2 [Figure 2: see original paper]). In the professional version, each model can run independently or provide a customized environment for coupled simulation of multiple models. In the decision-making version, the integrated functions of "monitoring-simulation-assessment-warning-decision-regulation" have been realized, with seven modules developed: monitoring and surveillance, non-point source pollution, water cycle, water ecology, shoreline, urban agglomeration, and regulation decision-making. In the monitoring module, real-time online water quality monitoring data from project demonstration areas and three lake experimental stations have been integrated and displayed, along with real-time hydrological monitoring data for the entire basin. In the water cycle module, spatiotemporal variation characteristics of the entire basin' s hydrological cycle over the past 40 years and the next 30 years have been simulated and analyzed. Based on 15-day short-term weather forecast data, rolling forecasts of basin hydrological regimes have been realized, forecasting runoff, soil moisture, and evapotranspiration changes in each hydrological response unit, flow and water level changes at key main stream sections, and water regime changes in Poyang Lake and Dongting Lake. In the lake/reservoir module, hydrological and hydrodynamic processes in Dongting Lake and Poyang Lake over the past 40 years and the next 30 years have been simulated, along with possible hydrological regime changes from Poyang Lake gate construction and its impacts on migratory bird habitats. In the shoreline module, evolution characteristics of landward and waterward shoreline quality in the middle and lower main stream have been obtained; a waterward shoreline quality assessment model based on flagship species finless porpoise habitat requirements has been established; and a landward shoreline pollutant interception spatial allocation model has been established to determine spatial allocation schemes for different types of landward shorelines, which have been applied to Yangtze River basin territorial spatial allocation planning. In the water ecology module, hydrological-hydrodynamic-food web models for typical river reaches have been established. In the urban water system module, coupled simulation of rainfall-runoff-water use-drainage-pollutant generation processes for the middle Yangtze River urban agglomeration and Chengdu-Chongqing urban agglomeration has been realized; hydrological effects of urbanization and urban waterlogging simulation have been conducted for typical cities (Chongqing, Wuhan); and based on future 24-hour hourly weather forecast data, rolling forecasts of waterlogging trends in Wuhan' s built-up area have been realized for application. In the regulation decision-making module, a basin green development evaluation model has been established to assess spatiotemporal differences in different dimensions of green development at the prefecture-level city scale, propose green development regulation schemes at the prefecture-level city scale, and simulate possible changes in basin non-point source pollution and their potential contributions to main stream water quality changes under different regulation schemes.

In terms of service system development, work has been carried out for public services, data applications, government decision-making, and comprehensive management technology. A public version mini-program of the Yangtze River Simulator has been developed to lay a foundation for public education and participation in Yangtze River protection. A comprehensive database for the Yangtze River Simulator has been constructed to support the professional, decision-making, and public versions of the platform and lay a foundation for scientific data sharing services in the Yangtze River basin. In terms of government decision-making services, important consultation suggestions have been provided for industry and regional management through consultation reports. In terms of basin comprehensive management technology services, key technologies for water ecological restoration in typical lakes/lake areas, comprehensive management of urban water environment and water ecology, and ecological restoration and regulation of Yangtze River main stream shorelines have been constructed, initially forming the service system of the Yangtze River Simulator.

The research and development concept of the Yangtze River Simulator serving scientific researchers, the public, and government decision-making, along with its development progress, has been recognized by the Chongqing Municipal Government. Under the strategic cooperation framework between the Chinese Academy of Sciences and the Chongqing Municipal Government, the Chongqing Municipal Government regards the construction and implementation of the Yangtze River Simulator as a scientific and technological tool to support ecological civilization construction in Chongqing and the entire Yangtze River basin. Support for the research, development, and implementation of the Yangtze River Simulator has been written into the *Chongqing Municipal National Economic and Social Development 14th Five-Year Plan and 2035 Vision Goals Outline* issued by the Chongqing Municipal Government in March 2021 and the *Chongqing Municipal Science and Technology Innovation "14th Five-Year" Plan (2021-2025)* issued in 2022. Both parties will strive to build the Yangtze River Simulator into a basin information comprehensive integration platform, basin water system evolution simulation platform, and basin comprehensive regulation management decision support platform, becoming another national-level major scientific and technological infrastructure in the ecological environment field.

3.2 Design for Water Ecological Operation of the Yangtze River Simulator

During the development of the Yangtze River Simulator, the ecological water level requirements of two large river-connected lakes (Dongting Lake and Poyang Lake), the response relationships of benthic animals, fish, and floodplain vegetation to river hydrological rhythms (flow, flow velocity) in typical main stream reaches, and the estuary saltwater intrusion flow requirements were considered. With flood control, power generation, and navigation requirements as constraints and based on the existing Three Gorges Reservoir operation scheme, a Three Gorges Reservoir ecological operation model was established. Six reservoir outflow control methods were set up, including hypothetical no-reservoir, existing optimized operation, planning and design operation, upstream water level control, discharge flow control, and ecological operation. Through joint simulation of different reservoir operation methods with basin distributed hydrological models, basin non-point source pollution models, main stream hydrodynamic-water quality models, river-connected lake hydrodynamic models, and river channel water ecological models, changes in water quality, hydrology, and water ecological processes in the main stream and river-connected lakes under different operation methods, as well as possible changes in aquatic organism habitats and different responses in food webs, were simulated and analyzed to determine appropriate water ecological operation schemes for the Three Gorges Reservoir.

4. Main River Channel Water Ecological Operation Based on the Yangtze River Simulator

4.1 Construction of Main River Channel Water Ecological Operation Model

The main river channel water ecological operation model of the Yangtze River Simulator is based on the hydrological periodic fluctuation process required for ecosystem service objectives, shifting from static to dynamic flow targets and from stimulating four major Chinese carp spawning to meeting fish full life history process requirements. This operation model is completed through joint simulation of basin hydrological models, Three Gorges Reservoir operation models, main stream one-dimensional hydrodynamic models, typical reach two-dimensional hydrodynamic models, and multiple typical reach hydrological-food web models in the Yangtze River Simulator. The specific process is shown in the appendix. Model input parameters are the Three Gorges Reservoir' s daily outflow on an annual basis, and output parameters are the resource quantities of multiple basic organisms (hygrophytic plants, emergent plants, phytoplankton, zooplankton, and benthic animals), fish resources, and potential finless porpoise numbers in multiple typical reaches. Basic organism resource quantity estimation is based on each basic organism' s requirements for water flow habitat factors (water depth, flow velocity) combined with two-dimensional hydrodynamic models for typical reaches to determine suitable areas for basic organisms, which are multiplied by biomass to obtain basic organism resource quantities in the reach. By comparing simulation results of different schemes, river channel water ecological effects under environmental changes—that is, the requirements of higher organisms for environmental conditions such as hydrology and habitat—are analyzed and used to optimize ecological operation of the Three Gorges Reservoir.

4.2 Application of Main River Channel Water Ecological Model Based on Three Gorges Operation

(1) Simulation of water ecological effects of actual operation mode after Three Gorges Reservoir impoundment. This study simulated and analyzed responses of aquatic organisms in main stream reaches under no-reservoir and with-reservoir conditions (actual operation mode). Compared with the no-reservoir scenario, the actual operation mode of the Three Gorges Reservoir leads to a 2.8% (0.5%-4.9%) reduction in fish and finless porpoise numbers, a 3% (0-5.8%) reduction in hygrophytic plant resources, a 5% (0.4%-8%) reduction in emergent plants, a 0.6% (0-2.2%) reduction in benthic animals, and minimal impact on plankton. The main reasons are that during low-water periods (February-March), increased water levels to meet navigation requirements reduce floodplain hygrophytic plant germination areas; during the pre-flood recession period (May 25-June 10), large water releases in a short period (reservoir water level dropped to 145 m on June 10) cause rapid river water level rise, which is unfavorable for floodplain hygrophytic plant growth. Additionally, fine sediment released from the Three Gorges Reservoir has caused intensified riverbed scouring in the middle and lower reaches, unstable substrate, and reduced benthic animal resources, which is also an important factor affecting fish resources.

(2) Proposed feasible optimal parameters for Three Gorges Reservoir ecological operation. Through comparison and selection of different operation schemes, while meeting flood control and navigation requirements and considering relationships between aquatic organisms and hydrological regimes in main stream reaches, the basic parameters for Three Gorges Reservoir ecological operation were preliminarily determined (Figure 3 [Figure 3: see original paper]). Discharge flow in February-March is 6,000-7,000 m^3/s, which can meet navigation requirements (minimum navigation requirement is 6,000 m^3/s) while maintaining relatively low flow to provide sufficient germination area for floodplain plants. Discharge flow in April is maintained at 7,000-8,000 m^3/s, in May at 8,000-13,000 m^3/s, and in June at 13,000-18,000 m^3/s, which can meet flood control requirements while having relatively small impacts on aquatic organisms. Specifically, during the flood season reservoir release period from April 15 to June 15, the reservoir capacity should be released as slowly as possible (daily increase less than 160 m^3/s) to provide sufficient growth periods for hygrophytic

plants. In May-June, when water temperature reaches 18°C-30°C (optimal 18°C-24°C), flood peaks should be created to meet four major Chinese carp spawning requirements, with daily water increase greater than 2,000 m^3/s, about 5 flood pulses, and total water increase greater than 10,000 m^3/s (short-term continuous flooding does not cause significant impact on floodplain plants). This scheme has been specifically reported to the Changjiang Water Resources Commission and the Three Gorges Cascade Dispatching Communication Center. The currently established Three Gorges Reservoir ecological operation scheme considers hydrological process requirements for the entire fish life history process in addition to fish spawning requirements. In late spring and early summer, flood peaks are created to promote reproduction of fish producing drifting eggs. After hatching, larvae need to reach slow-flow areas (flow velocity <0.03 m/s) (floodplains, river-connected lakes, etc.) to feed on zooplankton, where submerged vegetation can create low-flow-velocity habitats. Juvenile, subadult, and adult fish feeding on plankton, benthic animals, or aquatic plants also require low-flow-velocity environments. For fish producing adhesive eggs (such as carp, crucian carp, and topmouth culter) that need plants or sand as spawning substrates, if no suitable substrate exists in the water during spawning periods, water level rise is needed to allow parent fish to spawn in the water-land ecotone. Therefore, to increase total fish resources, ecological operation needs to meet requirements for all stages of the fish life history.

5. Simulation of Typical Water Regimes and Ecological Effects in River-Connected Lakes

The river-connected lake hydrodynamic model, based on fine topographic elevation of river-connected lakes and inflow/outflow discharge and water level information, can reflect outflow, backwater, and backflow effects between river-connected lakes and the Yangtze River. It simulates lake hydrodynamic changes under the combined effects of lake basin and Yangtze River inflow, characterizing dynamic wetting and drying processes of the water surface. It can be applied to assess impacts of river-lake relationship changes on lake hydrodynamics under different climate change and human activity influences, capture lake hydrodynamic fields in typical hydrological years and stages, and provide spatiotemporal variation datasets of lake hydrological and hydrodynamic elements for lake water ecology and wetland ecology research. Taking Poyang Lake as an example, simulated water depth spatial distribution during the 2006 low-water period well characterized the distribution pattern of deep channels, shallow beaches, deeper north and shallower south in Poyang Lake (Figure 4 [Figure 4: see original paper]). Fine simulation of lake hydrodynamic fields can be applied to waterway planning and habitat suitability assessment for migratory birds and other aquatic organisms.

5.1 Regulation Effects of Water Conservancy Hub Projects in River-Connected Lakes

Over the past 20 years, problems of low water levels, early dry seasons, and extended dry periods in Poyang Lake have become increasingly prominent, showing normalization and trend characteristics. Constructing the Poyang Lake Water Conservancy Hub Project is considered by local authorities as a "fundamental" solution. To meet assessment needs for the proposed Poyang Lake Water Conservancy Hub Project, the Poyang Lake hydrodynamic module has specifically added hub function definition and boundary characterization to conduct assessment calculations under both current conditions and post-construction scenarios. While considering that water conservancy hubs can effectively increase water resources, attention must be paid to potential water environment risks from reduced flow velocity and extended water exchange cycles. This study selected three typical years—2011 (dry year), 2016 (wet year), and 2017 (normal year)—to assess lake hydrological and hydrodynamic changes before and after gate construction. In terms of impact periods, the impoundment period in September and early recession period had the greatest impact. In dry years, the average water level across the lake increased by 1.52 m after gate construction compared with before, while in wet years the average water level increased by 1.07 m. In December, the average water level increase was less than 0.5 m. Spatially, gate construction mainly affected the northern, central, and eastern lake areas, with smaller impacts on western and southern areas. Hydrodynamic impacts were mainly concentrated in channel areas, where flow velocity generally decreased with larger reductions in front of the gate. In beach areas where flow velocity was already low and flow direction variable, sensitivity to the water conservancy hub was lower than in channel areas.

5.2 Simulation of Potential Habitats for Migratory Birds in River-Connected Lakes

The potential habitat model for migratory birds is based on the river-connected lake hydrodynamic model. Using water depth calculation results from the lake hydrodynamic model, potential habitats for migratory birds are automatically extracted by setting water depth thresholds. The water depth threshold for migratory bird habitats in river-connected lakes is set at 50 cm, basically including suitable water depths for all migratory bird habitat types in river-connected lakes. Considering migratory bird migration and residence times, the main calculation periods are January-February and November-December each year, while also considering the duration of suitable water depths. Based on hydrodynamic simulation results under different typical years and water conditions, spatial distributions and changes of suitable migratory bird habitats throughout the year under corresponding conditions can be calculated.

Taking 2006 as an example, suitable potential habitats for migratory birds in Poyang Lake were mainly distributed in central lake estuaries, nature reserves, and shallow lake bays (Figure 5a), consistent with previous reports. After water conservancy hub operation, water depth conditions changed, and the spatial distribution pattern of potential habitats adjusted accordingly, with slight decreases in central and eastern lake areas but substantial increases in western areas (Figure 5b). For extreme dry years, water level rise after gate construction inundated previously dry beach areas, effectively increasing suitable migratory bird habitat range.

6. Summary and Recommendations

6.1 Summary

The Yangtze River Simulator considers impacts of large reservoir operation on hydrological regimes in downstream river channels and river-connected lakes. It has constructed a Three Gorges Reservoir ecological operation scheme based on energy flow-food web relationships, shifting from static to dynamic flow targets and from stimulating four major Chinese carp spawning to meeting fish full life history process requirements. This has deepened the connotation of Three Gorges ecological operation. However, Three Gorges operation involves multiple aspects including flood control, power generation, navigation, ecology, and environment, requiring communication and cooperation among multiple departments. Power generation and navigation operation modules in the model are relatively simple and need further deepening in the future. Joint operation of cascade reservoirs above the Three Gorges requires both joint water quantity regulation and specific water ecological protection objectives and basic requirements for aquatic organisms in specific river reaches, requiring further in-depth research and development of corresponding hydrodynamic-water ecology coupling simulation modules.

Water ecological problems in river-connected lakes in the middle and lower Yangtze River are also affected by the combined effects of multiple downstream water conservancy projects, requiring in-depth research on joint ecological operation of the Three Gorges Reservoir and downstream water conservancy projects. For example, water ecological operation in Poyang Lake involves not only Three Gorges operation but also joint operation of upstream water conservancy projects in the Gan River basin. The migratory bird habitat suitability assessment model developed based on river-connected lake hydrodynamic models can simulate and analyze possible impacts of different operation methods and gate construction on hydrological regimes and migratory bird habitats in river-connected lakes. However, current lake models still lack hydrodynamic-water quality coupling simulation capabilities and cannot simulate spatiotemporal differentiation characteristics of water quality impacts from altered hydrodynamic environments. Water ecological process simulation has only considered migratory bird habitats, which is relatively simplified. Future lake hydrodynamic-water quality-water ecology coupling simulation will be an important direction. Currently, water quality simulation in river-connected lakes downstream of non-point source pollution models depends on the accuracy of non-point source pollution simulation. The Yangtze River Simulator has preliminarily developed basin non-point and point source pollution simulation models that can finely express differences in runoff path impacts on pollutant migration processes, identify critical source areas and critical periods of pollutants, and directly meet management and control needs. However, due to limitations in water quality monitoring data sharing and insufficient fine spatial information on point source pollution distribution, simulation accuracy still has considerable room for improvement.

The current Yangtze River Simulator can only be considered as the first-generation device for large basin simulation, still far from the planned goals and theoretical framework. Capacity improvements in water ecological operation for the Yangtze River Simulator require greater efforts in description capability, computing capability, big data aggregation and processing capability, human process modeling, and intelligent regulation decision-making. In the field of scientific and technological innovation, continuous development and improvement of specialized models and modules will be a long-term task for Yangtze River Simulator research and development. In terms of basin comprehensive management and government decision-making support, developing application examples for different departments and levels, deeply understanding user needs, and improving application function development are necessary. In the field of public education and participation, further understanding public needs and developing relevant functions for the public version is an important task for ecological protection in the Yangtze River basin and a key function of the Yangtze River Simulator.

6.2 Recommendations

During the development of the Yangtze River Simulator, the promulgation and implementation of the *Yangtze River Protection Law* have deeply impressed upon us the importance of inter-departmental and inter-governmental coordination and basin-wide planning in Yangtze River basin ecological protection, while the lack of strong scientific and technological support is a key problem facing water ecological protection in the Yangtze River basin.

(1) It is recommended to include the Yangtze River Simulator in national major scientific and technological infrastructure construction as soon as possible. Giving play to the leading role of scientific and technological innovation is key to promoting systematic governance and green development of the Yangtze River basin. Basin simulators have become an important innovation direction for the International Association of Hydrological Sciences (IAHS) third decade plan. The Yangtze River Simulator is the world's first large basin simulation device, with participation from more than 10 research institutions including the Chinese Academy of Sciences, universities, and departmental research institutes. It represents an important embodiment of optimized combination of science and education resources and collaborative innovation cooperation, enhancing original innovation capabilities in basin water system science. In supporting the construction

of major Yangtze River Simulator infrastructure, the country can rely on the Yangtze River Simulator to build a Yangtze River basin scientific data center, achieve interconnection of different industries and different types of data, break industry data sharing barriers, and by coupling different monitoring technologies, model methods, and governance and disaster management technologies, realize cross-industry and cross-departmental model integration to create an open and expandable coupled integration major scientific device. This will enhance innovation capabilities in basin water system scientific research, serving high-quality green development of the Yangtze River Economic Belt.

(2) It is recommended to conduct research and experiments on joint ecological operation of the Three Gorges Reservoir, upstream reservoirs, and reservoirs in the two lake basins. Considering that Three Gorges operation impacts on the two lakes have strong spatiotemporal heterogeneity, with relatively significant effects in East Dongting Lake and northern Poyang Lake but limited short-term effects, research and experiments on joint ecological operation of the Three Gorges Reservoir and upstream and two-lake basin reservoirs are recommended. In addition, large floodplain wetlands in the two lakes serve as spawning grounds for fish producing adhesive eggs and important habitats for overwintering migratory birds, and their inundation and exposure change dynamically. During ecological operation, beach area and water level changes also require close attention. Future research on ecological effects superposition from joint ecological operation on hydrological connectivity, water exchange, and water environment still needs deepening.

(3) Conduct ecological operation experiments for the Three Gorges Reservoir for fish and finless porpoise protection relying on the Yangtze River Simulator as soon as possible. The Yangtze River Simulator has coupled the Three Gorges operation model, Yangtze River middle and lower reaches main stream one-dimensional hydrodynamic model, typical reach hydrological-hydrodynamic-food web model, lake hydrodynamic model, and migratory bird potential habitat model, which can be used to conduct ecological operation experiments in the Yangtze River basin. However, due to scattered and difficult-to-obtain high-precision underwater topographic data for rivers and reservoirs, it is recommended to integrate national advantageous forces to centrally develop "hydrological-hydrodynamic-food web" models to provide scientific support for continuous improvement of ecological operation work.

References

1. Sato T. The earth simulator: Roles and impacts. *Parallel Computing*, 2004, 30(12): 1279-1286.
2. Dunne J P, John J G, Shevliakova E, et al. GFDL' s ESM2 global coupled

climate-carbon earth system models. Part I: Physical formulation and baseline simulation characteristics. *Journal of Climate*, 2012, 25(19): 6646-6665.

3. Golaz J C, Caldwell P M, Van Roekel L P, et al. The DOE E3SM coupled model version 1: Description and results at high resolution. *Journal of Advances in Modeling Earth Systems*, 2019, 11(12): 4095-4146.
4. Beusch L, Gudmundsson L, Seneviratne S I. Emulating Earth system model temperatures with MESMER: From global mean temperature trajectories to grid-point-level realizations on land. *Earth System Dynamics*, 2020, 11(1): 139-159.
5. Zeng Q C, Lin Z H. Recent progress on the earth system dynamical model and its numerical simulations. *Advances in Earth Science*, 2010, 25(1): 1-6. (in Chinese)
6. Yu G R, Zhang L, He H L, et al. A process-based model and simulation system of dynamic change and spatial variation in large-scale terrestrial ecosystems. *Chinese Journal of Applied Ecology*, 2021, 32(8): 2653-2665. (in Chinese)
7. Xia J, Zhan C S, Zeng S D, et al. Theoretical method and practical exploration of Yangtze River Simulator construction. *Journal of Hydraulic Engineering*, 2022, 53(5): 505-514. (in Chinese)
8. Yang L H, Zeng S D, Xia J, et al. Effects of the Three Gorges Dam on the downstream streamflow based on a large-scale hydrological and hydrodynamics coupled model. *Journal of Hydrology: Regional Studies*, 2022, 40: 101039.
9. Wang H Z. On the overall protection strategy of water ecological environment in the Yangtze River Basin (preface). *Acta Hydrobiologica Sinica*, 2019, 43(S1): 1-2. (in Chinese)
10. Ma Q, Li R, Feng J J, et al. Ecological regulation of cascade hydropower stations to reduce the risk of supersaturated total dissolved gas to fish. *Journal of Hydro-environment Research*, 2019, 27: 102-115.
11. Wang J, Su W, Yang S R, et al. Variation characteristics of fish biodiversity in Suijiang section before and after impoundment of first phase of Jinsha River hydropower project. *Resources and Environment in the Yangtze Basin*, 2017, 26(3): 394-401. (in Chinese)
12. Meng B, Zhang J F, Ye H, et al. Current situation and protection enlightenment of the function of fishing spawning grounds in the national nature reserve for the rare and endemic fishes, upper reaches of the Yangtze River. *Resources and Environment in the Yangtze Basin*, 2019, 28(11): 2772-2785. (in Chinese)

13. Wang H Z, Liu X Q, Wang H J. The Yangtze River-floodplain ecosystem: Multiple threats and holistic conservation. *Acta Hydrobiologica Sinica*, 2019, 43(S1): 157-182. (in Chinese)

14. Hu Z P, Lin Y R. Analysis of evolution process and driving factors for aquatic vegetations of Poyang Lake in 30 years. *Resources and Environment in the Yangtze Basin*, 2019, 28(8): 1947-1955. (in Chinese)

15. Dong R, Wang Y Y, Lü C, et al. Effects of hydrological connectivity on the community structure of macrobenthos in West Dongting Lake. *Acta Ecologica Sinica*, 2020, 40(22): 8336-8346. (in Chinese)

16. Wang C M, Huang D Z, Zhang Y, et al. Assessment of integrity of macrobenthos in Lake Dongting (1988-2021) and impacts from environmental stress. *Journal of Lake Sciences*, 2023, 35(5): 1765-1773. (in Chinese)

17. Cheng G W, Chen G R. Ecological operating experiment for Three-Gorge Reservoir, creating healthy stream environment for Changjiang River. *Journal of Hydraulic Engineering*, 2007, 38(S1): 526-530. (in Chinese)

18. Guo W X, Xia Z Q, Wang Y K, et al. Ecological operation goals for Three Gorges Reservoir. *Advances in Water Science*, 2009, 20(4): 554-559. (in Chinese)

19. Xu W, Jin Y, Chen G Y, et al. Changes of natural reproduction of fish producing drifting eggs in downstream Shashi section, middle reaches of Yangtze River during the ten-year (2011-2020) ecological operation of Three Gorges Reservoir. *Journal of Lake Sciences*, 2023, 35(5): 1729-1741. (in Chinese)

20. Ding H L, Cheng M M, Hu Y G, et al. Understanding and practice of ecological operation in Danjiangkou-Wangfuzhou section in Hanjiang River. *Yangtze River*, 2022, 53(3): 74-78. (in Chinese)

XIA Jun, Academician of the Chinese Academy of Sciences (CAS); Foreign Member of the Norwegian Academy of Sciences; Professor and Director of the Research Institute for Water Security at Wuhan University, China. His main research areas include system hydrology, sustainable utilization of water resources, eco-hydrology, and climate change impact and adaptive water management. E-mail: xiajun666@whu.edu.cn

LIN Zhonghui, Associate Professor of Institute of Geographic Sciences and Resources Research, Chinese Academy of Sciences (CAS). His main research field is focused on eco-hydrology. E-mail: linzh@igsnrr.ac.cn

*Corresponding author

Note: Figure translations are in progress. See original paper for figures.