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Study on the joint operation scheme of key water conservancy projects in the Taihu Lake Basin: a case study on ensuring flood control safety

Li Tang, Lili Gong*

Water Resources Development Research Center, Shanghai, China

*Corresponding Author. E-mail: 673236158@qq.com

Abstract. In response to the severe flood control challenges in the Taihu Lake Basin, this study focuses on the coordinated operation of newly constructed projects—such as the Xinmeng River and Xingou River—and the existing water conservancy system. Addressing the drainage difficulties in the upstream Huxi Area and the Wucheng–Xixi–Yuxi Area, the research adopts a technical framework of "scenario-driven analysis–scheme simulation–multi-objective decision-making." Through simulation and optimization based on mathematical models and an intelligent decision-support system, an operationally feasible joint operation scheme is proposed. The results demonstrate that optimized joint operation can significantly unleash the flood control potential of water conservancy projects, providing valuable methodological insights and a practical reference for coordinated operation and intelligent decision-making in complex river network regions.

Keywords: Taihu Lake Basin, joint operation, flood control safety, multi-objective decision-making, water quantity and quality models

1. Introduction

With global climate change and rapid socioeconomic development, issues such as water scarcity, increasingly frequent flood disasters, and the deterioration of aquatic ecosystems have become more pronounced. In large river basins, water conservancy projects are interlinked and mutually influential, forming complex mega-systems characterized by multiple objectives, multiple constraints, and high-dimensional nonlinearity [1, 2]. To maximize the comprehensive benefits of water resources utilization and to achieve coordinated development across objectives including flood control, water supply, power generation, navigation, and ecological protection, the joint optimal operation of water conservancy projects within complex river networks has emerged as a core issue and a key technical challenge in modern water resources management [3]. Traditional operation strategies designed for single reservoirs or simple systems can no longer meet the demands of refined water resources management. Joint operation in complex river networks seeks, through systematic optimization approaches, to coordinate the operation of individual nodes within the network in order to achieve a global optimum or a satisfactory solution at the system level [4].

Flood control and disaster mitigation constitute the primary functions of water conservancy projects. Against the backdrop of increasingly frequent extreme weather events, research on joint flood control operation in complex river networks has become particularly critical. In recent years, studies in this field have shown a clear shift from traditional deterministic, single-objective optimization toward multi-objective, risk-informed decision-making that accounts for uncertainty. The spatial scale of analysis has expanded from individual reservoirs to large reservoir groups and entire river basins [5], while multi-objective optimization theories have been widely introduced into flood control operation research [6].

As the core region of the Yangtze River Delta, the Taihu Lake Basin is characterized by high urban density and concentrated economic assets, making water security assurance of paramount importance. The basin features a dense river network, mild channel gradients, slow flow velocities, and is subject to tidal backwater effects from both the Yangtze River and Hangzhou Bay. It is a classical example of a complex river–lake system, where flood control and drainage conditions have long been severe. The upstream Huxi Area and the Wucheng–Xixi–Yuxi Area experienced consecutive record-breaking heavy rainfall events in 2015 and 2016, resulting in tremendous flood control pressure. At the same time, along the Beijing–Hangzhou Grand Canal, intensified urban enclosure has sharply increased drainage demands, further exacerbating flood-related conflicts. In recent years, a new round of basin management projects—represented by the Xinmeng River and the Xingou River—has been successively put into operation, providing new tools for basin-wide regulation while also raising new challenges regarding coordinated optimization with the existing project system. Therefore, conducting research on joint operation technologies for water conservancy project systems aimed at ensuring flood control safety, and proposing scientifically sound and operationally feasible optimization schemes, is of great practical significance and theoretical value for systematically enhancing flood control and disaster mitigation capacity in the Taihu Lake Basin.

2. Research framework and methods

2.1. Overview of the study area

The Taihu Lake Basin is bordered by the Yangtze River to the north, Hangzhou Bay to the south, the Tianmu Mountains to the west, and the East China Sea to the east. It forms a dish-shaped low-lying terrain centered on Taihu Lake. Characterized by an extensive network of rivers and a high density of lakes, the basin is a classical plain river network region. As the central hub for water storage and regulation within the basin, Taihu Lake plays a decisive role in flood control, water supply, and ecological security through its water level regulation. The water conservancy system examined in this study comprises the 11 key backbone projects implemented during the first phase of comprehensive basin management (such as the Wangyu River and the Taipu River), as well as several recently completed projects, including the Xinmeng River extension and channel widening project, the Xingou River extension and channel widening project, and the western bank control project of the Wangyu River. Together, these projects form a macro-scale regulation and drainage pattern characterized by "diverting water from the Yangtze River in the north, discharging to Hangzhou Bay in the south, conveying flows eastward to the Huangpu River, and relying internally on regulation and storage by Taihu Lake." The current operation rules are mainly based on the Flood and Water Quantity Operation Scheme for the Taihu Lake Basin.

2.2. Research methods

Following a full-process technical route of "scenario-driven analysis–scheme simulation–multi-objective coordinated decision-making and selection," this study adopts a scenario analysis approach that considers wet, normal, and dry rainfall conditions across the Taihu Lake Basin. With the enhancement of regional flood control safety as the primary objective, a set of joint operation schemes for the water conservancy project system oriented toward flood control security is constructed. Building on the integration of multi-objective coordinated operation scheme simulation and optimized decision-making techniques, the Taihu Lake Basin water quantity and water quality mathematical model is employed to conduct simulation calculations for the scheme set. The flood control and water security performance of each scheme is comprehensively evaluated, on the basis of which an optimized joint operation technical scheme for the basin-wide water conservancy project system is selected and proposed.

3. Design of the joint operation schemes

3.1. Objectives of operation optimization

At present, the Taihu Lake Basin has preliminarily formed a backbone water conservancy system featuring northward connectivity to the Yangtze River, eastward discharge to the Huangpu River, and southward drainage to Hangzhou Bay. However, during the flood season, the water level of Taihu Lake tends to rise rapidly but recedes slowly. Floodwaters in the upstream Huxi Area are difficult to discharge, resulting in prolonged periods of high water levels. Meanwhile, along the Beijing–Hangzhou Grand Canal, drainage capacity has continued to increase and now far exceeds the canal's safe conveyance capacity. Consequently, new challenges have emerged in basin-wide and regional flood regulation and drainage, creating an urgent need to expand drainage outlets for the upstream areas of the basin as well as for regions along the Grand Canal. The design of the present joint operation scheme is grounded in the objective of ensuring regional flood control safety across the basin. Research is conducted along two principal directions: expanding external drainage capacity for the basin and fully exploiting the regulating and storage function of Taihu Lake. The study on expanding external drainage focuses primarily on the operation of the Xinmeng River and Xingou River projects, with the aim of increasing northward drainage from the upstream Huxi Area and the Wucheng–Xixi–Yuxi Area to the Yangtze River, thereby maximizing the benefits of newly constructed backbone projects. The utilization of Taihu Lake's regulation and storage capacity is mainly oriented toward pre-flood-season drawdown. Relying on basin-administered projects such as the Wangyu River and the Taipu River, as well as key water conservancy projects along the Yangtze River and Hangzhou Bay, this study explores operational modes for the pre-discharge of Taihu Lake to achieve a reduction in lake water levels prior to the flood season.

3.2. Operation scenarios and boundary condition settings

The design of boundary conditions for the operation study primarily considers two factors: rainfall and the Yangtze River tidal level. To scientifically evaluate the flood control performance of the operation schemes, it is necessary to establish a representative and relatively unfavorable operation scenario. In this study, the "1991 Northern Basin" 1-in-100-year design rainfall, as specified in the Flood Control Plan for the Taihu Lake Basin, is adopted as the basin-wide rainfall condition. This rainfall pattern effectively represents extreme rainstorm scenarios affecting the Huxi Area and the Wucheng–Xixi–Yuxi Area. The basin-wide average rainfall over 90 days is 975.1 mm, while the corresponding 90-day average rainfall for the Huxi Area and the Wucheng–Xixi–Yuxi Area is 1,019.31 mm and 995.3 mm, respectively.

With respect to external boundary conditions, a comparison between the observed tidal levels in 1991 and the design tidal levels indicates that the observed peak tidal levels in 1991 were higher and thus more unfavorable for drainage through estuarine outlets along the Yangtze River. Based on the "relatively unfavorable principle," the observed Yangtze River tidal levels of the typical year 1991 are therefore adopted as the boundary conditions for the model simulations in this study, as summarized in Table 1.

Table 1. Boundary conditions for the joint operation study

Taihu Lake Basin Rainfall	Typical Year for the Basin	Yangtze River Boundary for the Taihu Lake Basin
"1991 Northern Basin" 1-in-100-year design rainfall	1991	Observed tidal levels of the typical year

3.3. Analysis of reference stations for operation and optimization periods

The scientific selection of reference stations is a prerequisite for formulating effective operation schemes. In accordance with the Technical Report on the Study of Water Resources Operation Schemes in the Taihu Lake Basin, and taking into account both compatibility with the existing operation of estuarine outlets along the Yangtze River in the Huxi Area and operational feasibility, the Fangqian Station is selected as the reference station for the operation of the Xinmeng River project. To better coordinate regional drainage and waterlogging control, the operation reference stations for the Xingou River project are set as the Zhuwu Area water level (Daixi), Changzhou (III), and Wuxi (Da).

With respect to the optimization period, considering the historical occurrence pattern of the highest water levels in Taihu Lake—which are mainly concentrated between June and October—as well as the probability of regional high water levels, the flood season (May to September) is identified as the key period for optimizing flood control operation of the Xinmeng River and Xingou River projects.

3.4. Optimization strategies and construction of scheme sets

3.4.1. Optimization scheme set for the Xinmeng River project

The preliminary design report of the Xinmeng River extension and channel widening project specifies that when the Taihu Lake water level is within the flood control operation zone, the reference water level for drainage operation of the Xinmeng River project is a Fangqian water level exceeding 4.2 m. Based on this operation rule, simulations are conducted under the "1991 Northern Basin" 1-in-100-year rainfall scenario to assess regional flood control risks in the basin. When the Taihu Lake water level exceeds the flood control limit, the occurrences of water levels exceeding the warning threshold at major stations in the Huxi Area are summarized in Table 2. The results indicate that stations such as Fangqian, Jintan, Wangmuguan, and Changzhou (III) generally experience prolonged periods above warning levels. In particular, the durations above the warning level at Fangqian and Changzhou (III) reach 53 days and 35 days, respectively.

Table 2. Number of days with water levels exceeding warning levels at major stations around the Xinmeng River during the Taihu Lake flood control operation period

Item	Jintan	Wangmuguan	Fangqian	Changzhou (III)
Warning water level (m)	5.0	4.6	4.1	4.3
Days exceeding warning level (days)	20	28	53	35

Therefore, to enhance the discharge of floodwaters from the Huxi Area to the Yangtze River and to reduce inflows from upstream areas into Taihu Lake, it is considered that there remains scope for further optimization of the reference water level for flood control operation of the Xinmeng River project, and that the Jiepai Water Control Hub should commence drainage earlier. The core optimization strategy for the Xinmeng River project is to lower the initiation water level for drainage at the Jiepai Water Control Hub during the flood season, with the aim of activating drainage in advance and creating a more favorable northward discharge pathway for floodwaters from the upstream Huxi Area and inflows from the Beijing–Hangzhou Grand Canal. A frequency analysis of the annual maximum water level at Fangqian Station shows that water levels of 4.6 m, 4.2 m, 4.0 m, and 3.8 m correspond to exceedance probabilities of P = 20%, P = 50%, P = 67%, and P = 83%, respectively. In combination with the frequency analysis and model simulation results, reference water levels of 4.0 m and 3.8 m at Fangqian Station are considered feasible options for drainage operation of the Xinmeng River project. Accordingly, the following set of operation schemes for the Xinmeng River project is proposed:

JC Scheme: When the Taihu Lake water level exceeds the flood control limit, sluice gates are opened for drainage when the Fangqian water level is ≥ 4.2 m, and pumps are activated for drainage when the Fangqian water level is ≥ 4.6 m.

FH1-XM1 Scheme: During the flood season, the sluice-gate drainage initiation level is lowered to a Fangqian water level of 4.0 m.

FH1-XM2 Scheme: During the flood season, the sluice-gate drainage initiation level is further lowered to a Fangqian water level of 3.8 m.

The operation of the regulating sluice at the Benniu Water Control Hub is adjusted accordingly. During periods when drainage is underway at the Jiepai Hub, the Benniu sluice may be opened as appropriate to divert floodwaters from the Beijing–Hangzhou Grand Canal.

3.4.2. Optimization scheme set for the Xingou River project

Following the implementation of the Xingou River extension and channel widening project, conditions have been created for northward discharge of floodwaters from the Zhuwu Area, allowing for further optimization of the regional flood control and drainage pattern. Optimization Strategy 1 focuses on increasing northward drainage of waterlogged flows from the Zhuwu Area. Under this strategy, the study investigates the feasibility of appropriately raising the reference water levels for drainage from the Zhihu Port Sluice and the Wujin Port Sluice into Taihu Lake, with the objective of promoting northward discharge of floodwaters while avoiding a significant increase in regional flood control pressure. Accordingly, reference water levels for discharge into Taihu Lake from the Zhuwu Area are raised to 4.7 m (close to the 10-year return period water level), 4.8 m (between the 10-year and 20-year return periods), and 4.9 m (close to the 20-year return period water level), respectively, to maintain northward flood discharge. Optimization Strategy 2 aims to enhance northward drainage of waterlogged flows from areas along the canal and surrounding regions. Building upon Strategy 1, this approach explores the potential for increasing the northward discharge capacity of the Xingou River project through coordinated operation with urban flood control projects in cities such as Changzhou and Wuxi. Based on the above strategies, the following set of operation schemes for the Xingou River project is proposed:

JC Scheme: When the water level in the Zhuwu Area (Daixi Station; same hereinafter) exceeds 4.5 m, sluice gates may be opened to discharge into Taihu Lake.

FH1-XG1, FH1-XG2, and FH1-XG3 Schemes: The control water level for discharge into Taihu Lake is raised to 4.7 m, 4.8 m, and 4.9 m, respectively.

FH1-XG4 Scheme: On the basis of the baseline scheme, coordinated operation with urban flood control in Changzhou (water level ≥ 4.3 m) and Wuxi (water level ≥ 3.8 m) is added. When the urban enclosure systems are activated, pumping stations at the riverside hubs and the Yaoguan North Hub are operated to enforce northward discharge.

FH1-XG5 Scheme: A combined application of Optimization Strategies 1 and 2, in which the control water level for discharge into Taihu Lake is raised to 4.8 m while coordinated operation with urban flood control systems in Changzhou and Wuxi is simultaneously implemented.

4. Model simulation and intelligent decision analysis

4.1. Model simulation calculations and results

4.1.1. Simulation results for the Xinmeng River scheme set

Under the "1991 Northern Basin" 1-in-100-year rainfall scenario, simulations were performed to obtain the corresponding water level processes (Figure 1). The simulated hydrographs indicate that, compared with the JC scheme, the FH1-XM1 and FH1-XM2 schemes both produce a marked reduction in regional peak water levels. In particular, under the FH1-XM2 scheme, the maximum water levels at Fangqian Station and Changzhou (III) Station are reduced by approximately 4–5 cm.

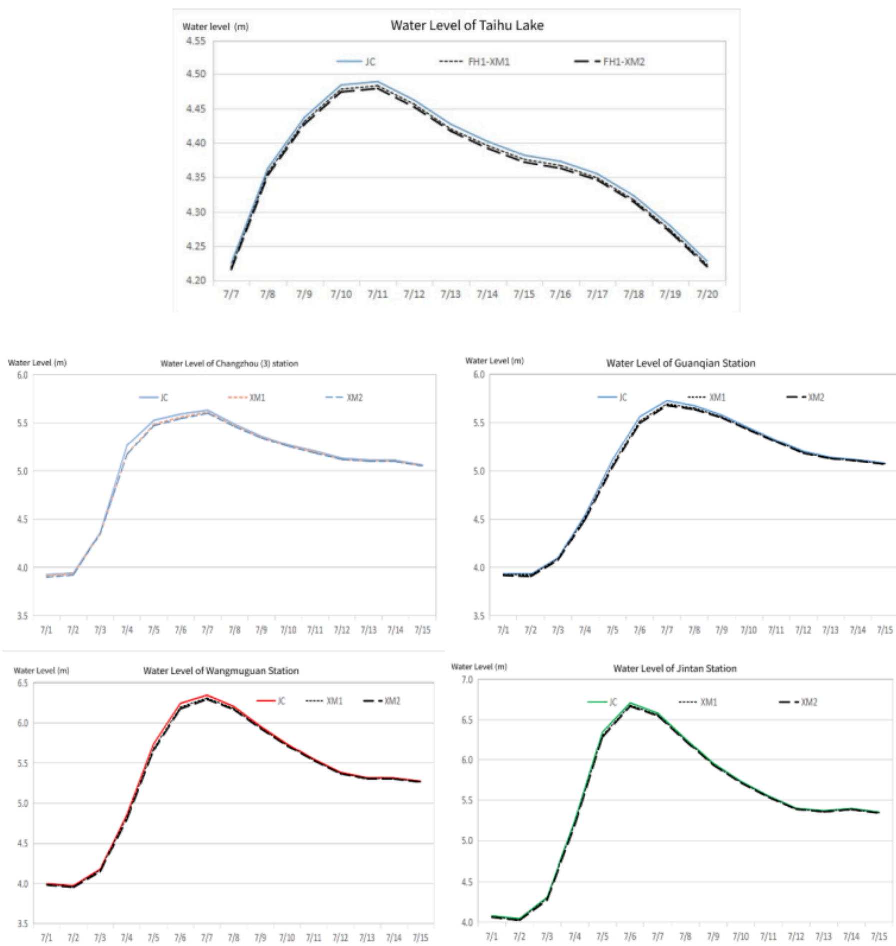

Figure 1. Water level hydrographs for the region and Taihu Lake under different schemes ("1991 Northern Basin" 1-in-100-year rainfall)

With respect to drainage discharge, the discharge hydrographs at the Jiepai Water Control Hub (Figure 2) clearly show that the optimized schemes—especially FH1-XM2—initiate drainage earlier and maintain drainage for a longer duration. During the flood season, the average discharge to the Yangtze River under the JC scheme is 75 m³/s, whereas this value increases to 82 m³/s under the FH1-XM2 scheme.

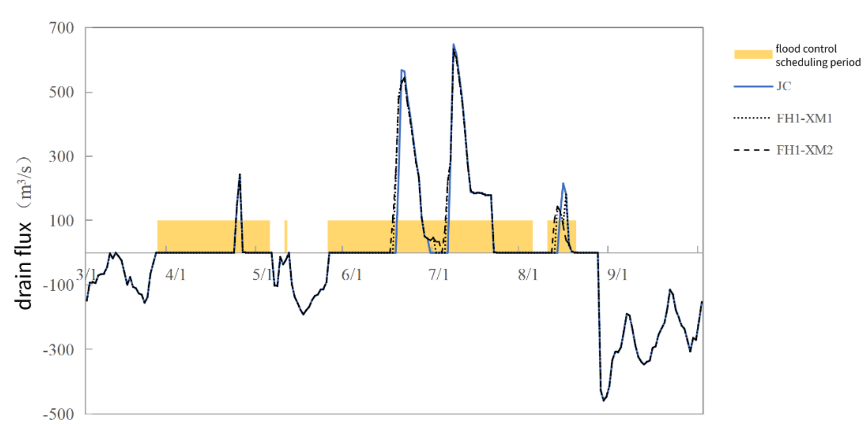

Figure 2. Drainage discharge hydrographs at the Jiepai Water Control Hub of the Xinmeng River under different schemes ("1991 Northern Basin" 1-in-100-year rainfall)

4.1.2. Simulation results for the Xingou River scheme set

The simulation results for the Xingou River schemes clearly illustrate the effects of different optimization strategies. Effects of Strategy 1: Under the FH1-XG1 to FH1-XG3 schemes, when the region is subjected to extremely large flood events, the impact on Taihu Lake water levels is relatively limited. However, if the control water level for discharge into the lake is raised excessively (e.g., to 4.9 m), a certain backwater effect is induced within the Wucheng–Xixi–Yuxi Area, leading to elevated internal water levels. Effects of Strategy 2 and the combined strategy: The FH1-XG4 and FH1-XG5 schemes, which incorporate coordinated operation with urban flood control systems, significantly enhance the northward drainage capacity. Under the FH1-XG5 scheme, the average discharge to the Yangtze River at the riverside hub of the Xingou River increases from 76 m³/s under the JC scheme to 85 m³/s (Figure 3), while inflows into Taihu Lake from the Zhuwu Area are substantially reduced.

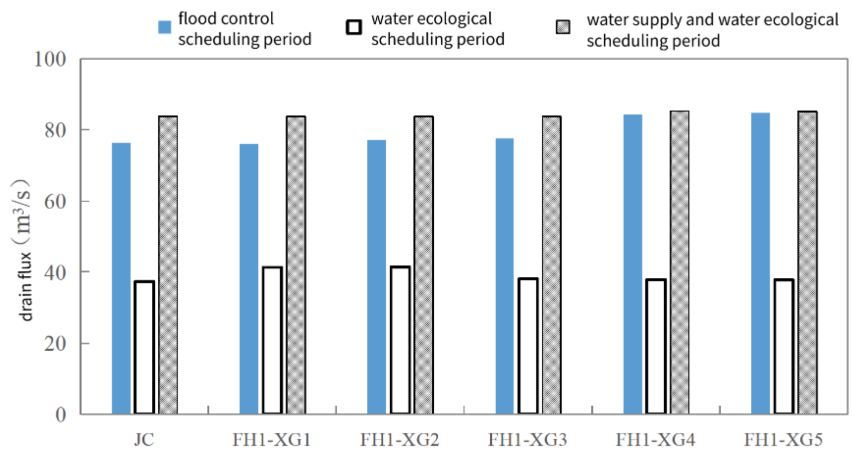

Figure 3. Drainage discharge at the riverside hub of the Xingou River under different schemes ("1991 Northern Basin" 1-in-100-year rainfall)

4.2. Intelligent decision-making for joint operation

4.2.1. Construction of the decision indicator system

To quantitatively evaluate the flood control benefits of the proposed schemes, the following core decision indicators are selected: (1) Drainage efficiency of key external discharge hubs: reflecting the drainage capacity of critical projects such as the Jiepai Hub of the Xinmeng River and the riverside hub of the Xingou River during the flood control operation period. (2) Risk of exceeding guaranteed water levels at representative flood control stations: characterizing the extent to which major water level stations in Taihu Lake and the surrounding regions exceed their guaranteed water levels. (3) Regional external drainage volume coefficient: indicating the effectiveness of external drainage (primarily discharge to the Yangtze River) from specific regions such as the Huxi Area and the Wucheng–Xixi–Yuxi Area.

4.2.2. Indicator normalization and objective function calculation

The raw model outputs—including discharge volumes, water levels, and durations—are normalized to values between 0 and 1 using specific algorithms, where 1 represents the optimal performance. Table 3 presents the normalized results of the evaluation indicators for the Xinmeng River scheme set during the flood control operation period.

Table 3. Normalized evaluation results of flood control indicators for the Xinmeng River schemes (flood control operation period)

Scheme	Operation Period	Drainage Efficiency of Key Hubs	Risk of Exceeding Guaranteed Levels at Representative Stations	Regional External Drainage Coefficient (WPi)	Pre-discharge Target Satisfaction (PY)
JC	Flood control operation period	0.37	0.44	0.40	1
FH1-XM1	Flood control operation period	0.85	0.87	0.83	1
FH1-XM2	Flood control operation period	0.92	1.00	0.92	1

The decision-support system aggregates the normalized indicators through weighted integration to compute the objective function value for each scheme across different operation periods. Based on the comprehensive annual decision results, the objective function values for the JC, FH1-XM1, and FH1-XM2 schemes are 94.4, 97.7, and 98.9, respectively. The FH1-XM2 scheme yields the highest objective function value and is therefore identified as the optimal scheme for the Xinmeng River project.

Applying the same decision-making procedure to the Xingou River scheme set indicates that the FH1-XG5 scheme achieves the highest objective function value (99.0), and is consequently selected as the optimal scheme for the Xingou River project.

4.3. Analysis of results

4.3.1. Analysis of water quantity regulation effects

A quantitative comparison of the water balance between the optimal schemes (FH1-XM2 and FH1-XG5) and the baseline scheme (JC) is presented in Table 4. The results demonstrate that the optimal schemes deliver pronounced benefits in terms of expanding external drainage and alleviating hydraulic pressure on Taihu Lake.

Table 4. Comparison of key water quantity indicators between the optimal schemes and the baseline scheme during the flood season

Statistic	JC	FH1-XM2	Change	JC	FH1-XG5	Change
Project discharge to the Yangtze River (10^8 m^3)	7.47	8.18	+9.5%	6.85	7.94	+15.9%
Regional inflow to Taihu Lake (10^8 m^3)	46.57	46.27	-0.6%	1.18	0.80	-32.7%
Regional discharge to the Yangtze River (10^8 m^3)	15.35	15.75	+2.6%	-	-	-

4.3.2. Benefits in flood control safety assurance

The implementation of the optimal schemes directly results in reduced water levels at both basin-wide and regional scales, as well as shorter durations of flood risk, as summarized in Table 5. Under the FH1-XM2 scheme, the maximum water levels at major stations in the Huxi Area are reduced by 4–5 cm. Under the FH1-XG5 scheme, the maximum water level of Taihu Lake is lowered by 1 cm without a noticeable increase in internal regional water levels, while the number of days exceeding warning levels at stations such as Changzhou (III) and Wuxi (Da) is reduced by 1–2 days. These results indicate that optimized joint operation enhances overall flood control safety in the basin while simultaneously achieving a synergistic outcome between basin-level flood control and urban flood protection.

Table 5. Impact of the optimal schemes on maximum water levels at representative stations (unit: m)

Station	JC	FH1-XM2	Change	FH1-XG5	Change
Taihu Lake	4.49	4.48	-0.01	4.48	-0.01
Fangqian	5.73	5.68	-0.05		
Changzhou (III)	5.64	5.60	-0.04	5.64	0.00
Wuxi (Da)	4.87			4.87	0.00

5. Conclusions

In response to the flood control safety requirements of the complex river network system in the Taihu Lake Basin, this study develops a joint operation scheme selection approach based on water quantity and water quality model simulations combined with multi-objective intelligent decision-making. Two core optimization strategies are proposed and validated. The first involves the implementation of "early drainage" for the Xinmeng River project by lowering the drainage initiation water level during the flood season from 4.2 m to 3.8 m. The second focuses on optimizing the Xingou River project by raising the control water level for the discharge of waterlogged flows from the Zhuwu Area into Taihu Lake from 4.5 m to 4.8 m, while establishing a coordinated operation mechanism with urban flood control projects in Changzhou and Wuxi. The model simulations and decision analysis demonstrate that, under the "1991 Northern Basin" 1-in-100-year rainfall scenario, the optimal schemes can significantly enhance basin-wide flood control performance. Specifically, discharges to the Yangtze River via the Xinmeng River and the Xingou River increase by 9.5% and 15.9%, respectively, effectively reducing upstream flood inflows into Taihu Lake and lowering the maximum water levels at Taihu Lake and key regional stations by 1–5 cm. The proposed schemes substantially alleviate flood control pressure in the upstream Huxi Area and along the Beijing–Hangzhou Grand Canal, optimize the overall basin drainage pattern, and provide scientifically robust and highly operational technical support for enhancing flood control and safety assurance capacity in the Taihu Lake Basin.

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