AQUA

Water Infrastructure, Ecosystems and Society

AQUA — Water Infrastructure, Ecosystems and Society Vol 73 No 3, 608 doi: 10.2166/aqua.2024.318

Research on the joint adjustment model of regional water resource network based on the network flow theory

Zhou Ye[a,*], Lin Ding[a], Zhisong Liu[b] and Fang Chen[a]

[a] School of Marine Engineering Equipment, Zhejiang Ocean University, Zhejiang, Zhoushan 316022, China
[b] School of Information Engineering, Zhejiang Ocean University, Zhejiang, Zhoushan 316022, China
*Corresponding author. E-mail: chidorikuu@foxmail.com

ABSTRACT

This study uses the network flow theory to optimize regional water resource allocation. In order to solve the problem of inefficient utilization of water resources with decentralized decision-making by different administrative units, a regional water resource networking and joint dispatching model with multi-objective nonlinear characteristics based on the network flow theory (hereinafter referred to as the network flow model) is constructed in the study. The network flow model was simulated and applied in the Xin-Sheng area of the Cao'e River, a tributary of the Qiantang River, and the results of the study showed that the network flow model scheduling increased significantly in efficiency compared with the current conventional scheduling, with an increase of 35.24 and 9.91% in the water resource utilization rate in the two typical years of 2019 and 2022, respectively, and showed that 2022, which has less rainfall, has a better effect than 2019. The study concludes that the network flow model can effectively improve the efficiency of water resource utilization, solve the problem of water resource imbalance between cities in the region, and play a positive role in the construction of the national water network.

Key words: mathematical models, network flows, networked joint commissioning, regional water resources

HIGHLIGHTS

- The aim of this study is to construct a network flow model based on nonlinear multi-objective optimization.
- Scheduling objective is to maximize water use under industry-dominated economic conditions.
- The network flow model couples incentive compatibility mechanisms between different administrative agents.
- Network flow modeling can test whether certain administrative units have over-exploited resources.

1. INTRODUCTION

In the 70 years since the establishment of the People's Republic of China, the country's water management efforts have seen rapid development, resulting in the formation of a comprehensive framework for water control projects. However, due to insufficient integration and systemization, regional issues such as localized water scarcity and uneven distribution of water resources persist. This paper employs a network flow approach to investigate the issue of regional water resource allocation equilibrium to further enhance existing and proposed projects. The application of network-related theories to modern water management both domestically and internationally has a history of just over a decade. One is to use remote sensing or geographic information system (GIS) technology to study water networks. Scholars employed GIS visualization techniques to simulate the spatial relationships of water resource systems and display their corresponding computational outcomes (Jain *et al.* 2000; Dibs *et al.* 2023) and explored a watershed water resource allocation study within a GIS-based framework (McKinney & Cai 2002). Part of research combined GIS spatial analysis models with mathematical models specific to water resources to address water resource issues (Manoj & Gupta 2003) and also investigated the generalization of water resource allocation models using GIS visualization technology and geometric network models (Dong *et al.* 2016). A portion of the study conducted quantitative research on river–lake water resource functions employing various technology combinations, including GIS, networks, and mathematical reasoning (Deng 2019). The second aspect of research focuses on project scheduling and river and lake connectivity (Wohl 2017), such as the study of structural connectivity (Zuo & Cui 2020; Chen *et al.* 2022) and the planar profile and distribution of natural river networks and their effects (Pringle 2003;

Wu & Wang 2022; Khalaf *et al.* 2023). The ecological significance (Freeman *et al.* 2007; Schmadel *et al.* 2018; Dou *et al.* 2022) and impacts of river network connectivity have also attracted much attention (Xiao *et al.* 2022; Yu *et al.* 2022). The third is the use of modern mathematical methods to study water resource allocation. Examples include the hydraulic connection of key nodes in the river network (Sarker *et al.* 2019; Li *et al.* 2021a, 2021b), the structure of water resource network constructed by the supply chain theory (Li 2010; Fu *et al.* 2017), and the development and optimization of water transmission and distribution network between reservoir clusters (Chen 2019; Zhou 2021; Bachtiar *et al.* 2023; Yao *et al.* 2023). In the above studies, the use of GIS to study the water system is mostly at the simulation level, and the study of water system connectivity is currently limited to the Yangtze River Delta Plain river network area, as for the use of the network flow study configuration has not actually become a real network.

Over the past 70 years since the founding of New China, the water control projects in each city jurisdiction have basically formed a framework. However, due to different river rain types, engineering resources, and rainfall, there are still differences in the utilization rate of water resources and water supply equilibrium between cities, so it is necessary to study the allocation of water resources from the perspective of the region as a whole. The authors have long studied the ancient water control projects in China and believe that the network flow idea is an important gene in the inheritance of the ancient regional water control in China, and the network flow idea contains the idea of ecological civilization and incentive-compatible mechanisms. This article presents the result of using the network flow theory to study the optimal allocation of regional water resources. The aim is to integrate water resources subject to decentralized decision-making allocations of different administrative units into the same regional network, maximize water resource utilization under industrial-led economic conditions, and construct a system based on nonlinear multi-objective optimization network flow network joint debugging model. This system makes full use of river hydrodynamic conditions and incentive compatibility mechanisms in dispatching.

2. NETWORK FLOW RESERVOIR CLUSTER INTERCONNECTED OPERATION MODEL

A regional reservoir group with Qiaoying Reservoir, Liaowan Reservoir, Changzhao Reservoir, Nanshan Reservoir, and Qincun Reservoir is established. The water levels (water storage capacity) of the five reservoirs are used as decision-making parameters, and the dispatched water volume between each reservoir is used as the decision-making variable. Taking reservoir safety, dispatch feasibility, and incentive maximization as constraints, and using the total water storage volume and water storage potential energy of the reservoir group as the objective function, a network flow model based on nonlinear multi-objective optimization is established. 2019 and 2022 were selected as typical years of wet and normal water years, and simulation dispatching experiments were conducted based on real hydrological data to compare the total water storage capacity of the reservoir group under conventional dispatch and network flow model dispatch. The results show that the network flow model can effectively solve the problems of uneven resource allocation and inefficient water use.

2.1. Symbol explanation

The symbols used in the model and their meanings are provided in Table 1.

2.2. Model assumptions

1) Based on the flow of the connecting river between the reservoirs and the water level difference between the reservoirs, and using river dynamics calculations, it is assumed that the maximum water transfer between the two reservoirs can reach 200,000 m^3 per hour and the maximum daily water transfer can reach 4.8 million m^3.

Table 1 | Symbol description

Symbol	Explanation	Unit
V	The total water supply received by all water treatment plants from the reservoirs per hour	10^4 m^3
W	The connectivity matrix for reservoir water transfers	/
H	The matrix represents the current water levels in the reservoirs	m
X	The matrix that specifies the flood control levels for the reservoirs	m
K	The matrix indicates the adjustable capacity or controllable volume of water within the reservoirs	10^4 m^3
G	The matrix is used for the inter-reservoir scheduling or dispatching operations	10^4 m^3

2) This paper studies water resource dispatching between reservoirs based on the natural hydrodynamic force of water level difference, so it is assumed that the dispatching cost between reservoirs can be ignored.
3) Each scheduling operation is assumed to involve the transfer of water between two reservoirs, prioritizing the self-flow type transfer to the reservoir with a lower water level.
4) Reservoir-to-water treatment plant supply operations are assumed to occur after inter-reservoir scheduling. Supply from reservoirs to water treatment plants can be organized based on administrative affiliations or economic relationships.
5) Ecological flow rates, as mandated by the provincial regulations, are automatically deducted before reservoir scheduling operations.

2.3. Model establishment

2.3.1. Establishment of the reservoir cluster scheduling model

Considering that real-time data available for each reservoir is the water level, while the scheduling operation for reservoirs is based on water volume, a mapping relationship is established between the current water level and the current capacity for each reservoir. Let $f_i(x)$ represent the discrete mapping from the water level to the capacity for the ith reservoir, and $g_i(x)$ represent the discrete mapping from capacity to water level for the ith reservoir. Specific numerical values for these mappings can be obtained through reference tables.

In the modeling and solution of the scheduling plan based on the current state of the reservoirs, we will analyze and model one stage, as the modeling approach for each stage is the same, differing only in initial conditions.

1) Introduction of decision variables:

Define the decision variable matrix $G = (G_{ij})_{5\times5}$, where G_{ij} represents the amount of water transferred from the reservoir j to the reservoir i.

2) Formulation of the optimization objective:

Assuming the current capacity of the ith reservoir is $f(H_i)$ and the capacity after scheduling is T_i, our objective is to maximize the total water storage of all reservoirs while also maximizing the potential energy of water in each reservoir through scheduling. Combining these two objectives, we introduce a weighting coefficient $0 \leq \lambda \leq 1$ and establish the optimization objective as follows:

$$\max \lambda \sum_{i=1}^{5} T_i + (1-\lambda) \sum_{i=1}^{5} X_i T_i \tag{1}$$

where $\sum_{i=1}^{5} T_i$ represents the total water storage capacity of the reservoir group consisting of five reservoirs, and $\sum_{i=1}^{5} X_i T_i$ represents the total potential energy of the reservoir group. This paper assumes that the water storage capacity and potential energy have equal weights, so it is taken λ as 0.5.

3) Formulation of constraint conditions:

The water level of each reservoir must not exceed the flood control level:

$$g_i(T_i) \leq X_i \tag{2}$$

Scheduling between two reservoirs should only occur from a higher water level to a lower water level:

$$(X_j - X_i) \cdot G_{ij} \geq 0 \tag{3}$$

The relationship for the water storage of the ith reservoir after scheduling is as follows:

$$f_i(H_i) + \sum_{j=1}^{5} G_{ij} - \sum_{j=1}^{5} G_{ji} = T_i \tag{4}$$

where $f_i(H_i)$ denotes the capacity of the ith reservoir before scheduling, $\sum_{j=1}^{5} G_{ij}$ denotes the sum of water transfers from other reservoirs to the ith reservoir, and $\sum_{j=1}^{5} G_{ji}$ denotes the sum of water transfers from the ith reservoir to other reservoirs.

Based on the above analysis, the mathematical model for reservoir scheduling is established as follows:

$$\max\ \lambda \sum_{i=1}^{5} T_i + (1-\lambda) \sum_{i=1}^{5} X_i T_i \tag{5}$$

$$\text{s.t.} \begin{cases} f_i(H_i) + \sum\limits_{j=1}^{5} G_{ij} - \sum\limits_{j=1}^{5} G_{ji} = T_i,\ i = 1,\ \cdots, 5 \\ g_i(T_i) \le X_i,\ i = 1,\ \cdots, 5 \\ (X_j - X_i) \cdot G_{ij} \ge 0 \\ G_{ij} \ge 0 \end{cases}$$

2.3.2. Model solution algorithm design:

1) Water transfer principles:

   a) The total water storage of all reservoirs is maximized.
   b) If the water level of any reservoir exceeds the flood control level, an immediate scheduling operation is initiated.
   c) The priority of scheduling based on the water levels of each reservoir is determined. When all reservoirs reach the flood control level, discharge operations are conducted by the Qinchuan Reservoir.

2) Determination of the reservoir scheduling period:

Based on the current reservoir scheduling principles, dynamic assessments of the scheduling plan are conducted on an hourly basis.

3) Determination of the reservoir scheduling connectivity matrix W:

Following the water transfer principles outlined in Section 1, the reservoirs are first ranked by their current water levels, from high to low, corresponding to $i = 1,\ \cdots, 5$. For the known flood control levels, a flood control level matrix can be established for each reservoir x. Given the known water levels, the current water level matrix H can be constructed for each reservoir. Furthermore, in conjunction with the water transfer principles provided in Section 1, a connectivity matrix for reservoir scheduling, denoted as W, is defined based on a Markov chain. The matrix W is defined as follows:

$$W_{ij} = \begin{cases} 1, & H_i \text{ is the second order of } H_j \\ 0, & \text{else} \end{cases} \tag{6}$$

In the above, where $i, j = 1,\ldots5$ represent the current water level ranking order of the reservoirs, and the connectivity matrix W is further adjusted dynamically to reflect the specific process of each scheduling operation, resulting in an updated connectivity matrix W.

4) The matrix representing the adjustable capacity of the reservoirs, denoted as the 'Reservoir Adjustable Capacity Matrix,' can be defined as follows:

$$K = (K_1, K_2,\ \cdots, K_5)^T \tag{7}$$

where K_i represents the adjustable water volume of the ith reservoir.

In reality, the transferable water volume K_i between various reservoirs is the portion of the current capacity $f_i(H_i)$ of certain reservoirs that exceeds their flood control capacity $f_i(X_i)$. In mathematical terms, this can be expressed as follows:

$$K_i = \begin{cases} f_i(H_i) - f_i(X_i), & H_i > X_i \\ 0, & H_i \le X_i \end{cases} \tag{8}$$

Based on the previous discussion, the inter-reservoir scheduling matrix G can be defined as follows: $G_i = W_i K_i$, where G_{ij} represents the volume of water transferred from one reservoir i to another j. In practice, the completion of a single scheduling operation requires an initial assessment of all reservoirs except for the Qinchuan Reservoir.

Considering that the current water levels of all reservoirs will not exceed their respective flood control levels, and the Qinchuan Reservoir has the lowest flood control level and does not transfer any water out. On the other hand, the Qiaoying Reservoir has the highest flood control level, and therefore, it does not receive any water.

Let A represent the inflow matrix for all reservoirs except the for Qinchuan Reservoir, and B represent the outflow matrix for all reservoirs except for the Qiaoying Reservoir. After a single scheduling operation, the current water level matrix for the reservoirs becomes $H = g_i(f_i(H) + A - B)$. Since the Qinchuan Reservoir only receives water transfers and, according to the scheduling principles, it needs to be assessed separately.

3. ANALYSIS OF SIMULATED SCHEDULING EXPERIMENTS

Over the past decade, the annual water consumption in Zhejiang Province has remained relatively stable at around 20 billion m^3. Water usage for residential, tertiary industry, and ecological purposes has steadily increased, while agricultural water usage has decreased year by year. Industrial water usage has experienced minor fluctuations. Zhejiang is an industrially driven province, and for this case, the study focuses on the Xinchang-Shengzhou area of the Cao'e River, a tributary of the Qiantang River (hereinafter referred to as the 'Xin-Sheng Area').

The Xin-Sheng Area includes five reservoirs participating in the simulated scheduling. The location of each reservoir is shown in Figure 1, and the characteristic values are shown in Table 2. Given that the Qinchuan Reservoir only became

Figure 1 | Relevant reservoir location map.

Table 2 | Characteristics of relevant reservoirs

Items	Qincun Reservoir	Changzhao Reservoir	Nanshan Reservoir	Liaowan Reservoir	Qiaoying Reservoir
Watershed area (km^2)	316	276	109.8	40.4	46
Total storage capacity (million m^3)	244	189	108	10.76	27.13
Normal storage capacity (million m^3)	176	13	69.87	9	20
Normal water level (m)	98	131.16	122.22	151.85	286.79
Flood control level (m)	96	124.26	119.72	148.0	286.79
Primary functions	Flood control, water supply, irrigation, power generation	Flood control, water supply, irrigation, power generation	Flood control, water supply, irrigation, power generation	Flood control, water supply, irrigation, power generation	Irrigation, flood control, water supply
Downstream protection area (mu)	193,100	130,000	100,000	Area along Changzhang-Yueqing and Shengzhou-Yiwu Road	
Irrigation area (mu)	18,400	100,000	89,000	2,000	57,600
Annual power output (million kWh)	5.2	16.5	8.20	3	7.5

operational in 2018, the years 2019 and 2022 were selected as typical years for wet and normal hydrological conditions, respectively. The simulated scheduling period spans from April 1st to October 31st of the respective years.

3.1. Simulated scheduling experiment in 2019

The simulated scheduling experiments involved retrieving hydrological data from the five reservoirs for the period from April 15, 2019 to October 31, 2019. According to the scheduling model, a total of 24 scheduling operations were executed during the flood season, resulting in a cumulative water transfer of 54.38 million m^3.

As a result of the simulated scheduling, by the end of the flood season on October 31st, the reservoir capacities for Qiaoying Reservoir, Liaowan Reservoir, Changzhuo Reservoir, Nanshan Reservoir, and Qinchuan Reservoir were adjusted as follows:

- Qiaoying Reservoir: Adjusted from 1,228.72 to 1,244.32 million m^3.
- Liaowan Reservoir: Adjusted from 624.70 to 764.02 million m^3.
- Changzhuo Reservoir: Adjusted from 7,740.60 to 11,969.31 million m^3.
- Nanshan Reservoir: Adjusted from 5,545.00 to 6,467.72 million m^3.
- Qinchuan Reservoir: Adjusted from 12,772.72 to 15,352.54 million m^3.

The flood discharge volumes for these reservoirs were also adjusted as follows:

- Qiaoying Reservoir: Adjusted from 1,187.53 to 1,089.53 million m^3.
- Liaowan Reservoir: Adjusted from 486.09 to 403.68 million m^3.
- Changzhuo Reservoir: Adjusted from 18,019.12 to 11,665.87 million m^3.
- Nanshan Reservoir: Adjusted from 2,847.92 to 2,379.46 million m^3.
- Qinchuan Reservoir: Adjusted from 18,045.76 to 15,047.83 million m^3.

For detailed information, refer to Table 3.

The Sankey diagram of the regional reservoir group water resources network joint adjustment in 2019 is shown in Figure 2.

Table 3 | Comparison of 2019 reservoir simulation scheduling data

	Initial state (April 15th)		**Termination state – no scheduling (October 31st)**			**Termination state – with scheduling (October 31st)**			**Comparison before and after scheduling**	
Reservoir name	**Water level**	**Water volume**	**Water level**	**Water volume**	**Flood discharge volume**	**Water level**	**Water volume**	**Flood discharge volume**	**Water volume**	**Flood discharge volume**
Qiaoying	283.44	1,633.25	279.23	1,228.72	1,187.53	279.41	1,244.32	1,089.53	−15.60	98.01
Liaowan	142.68	587.00	144.04	624.70	486.09	148.35	764.02	403.68	−139.32	82.40
Changzhao	126.66	1,0735.00	121.14	7,740.60	18,019.12	129.32	12,389.31	11,665.87	−4,648.71	6,353.25
Nanshan	121.49	6,794.00	116.55	5,545.00	2,847.92	120.22	6,460.63	2,379.46	−915.63	468.45
Qincun	94.24	14,556.12	91.88	12,772.72	18,045.76	97.10	16,889.63	15,047.83	−4,116.91	2,997.94
Total	/	/	/	27,911.74	40,586.41	/	37,747.91	30,586.37	−9,836.17	10,000.05

Note: The units in the table are as follows: water level: meters (m); water volume: cubic meters (m^3); flood discharge volume: cubic meters (m^3).

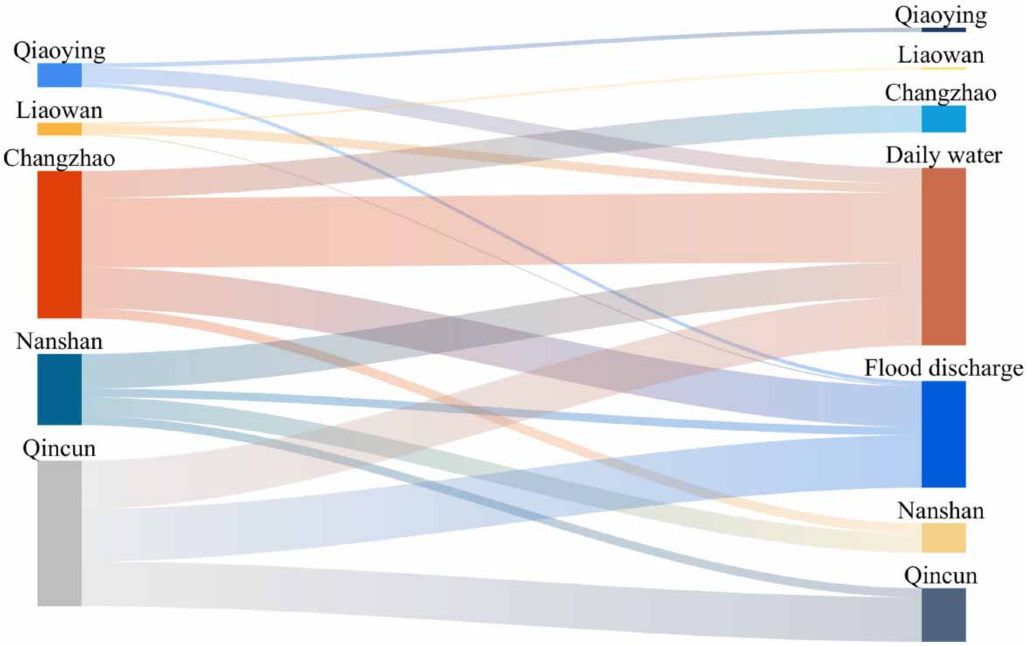


Figure 2 | 2019 Sankey diagram showing the network's collaborative management of regional reservoir group water resources.

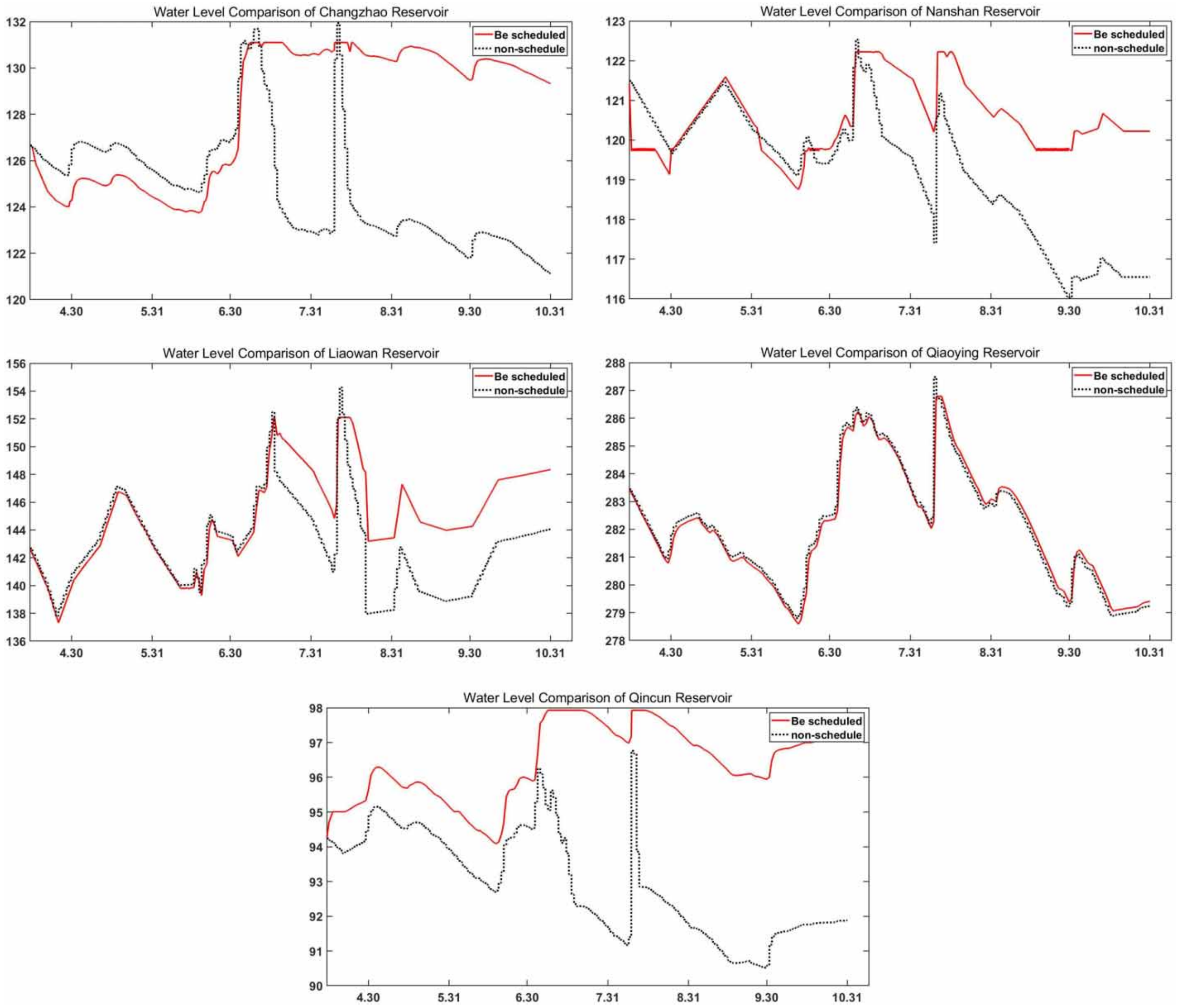
By comparing the hydrological data of the five reservoirs before and after the simulated scheduling, it was observed that the total water storage increased by 98.36 million m^3, representing a 35.24% increase compared to conventional scheduling. Additionally, the total flood discharge volume decreased by 100.05 million m^3, resulting in a 24.64% reduction compared to conventional scheduling. This indicates a significant improvement in water resource utilization efficiency.

The comparisons of water levels, water storage, and flood discharge volumes for each reservoir before and after the simulated scheduling are depicted in Figures 3–5.

3.2. Simulated scheduling experiment in 2022

Using hydrological data from April 15, 2022 to October 31, 2022, a simulated scheduling process was conducted. According to the scheduling model, a total of 19 scheduling operations were carried out during the flood season, resulting in a cumulative water transfer of 2,582.73 million m^3.

Following the simulated scheduling, by the end of the flood season on October 31st, the reservoir capacities for Qiaoying Reservoir, Liaowan Reservoir, Changzhuo Reservoir, Nanshan Reservoir, and Qinchuan Reservoir were adjusted as follows:


Water Level Comparison of Changzhao Reservoir

Water Level Comparison of Nanshan Reservoir

Water Level Comparison of Liaowan Reservoir

Water Level Comparison of Qiaoying Reservoir

Water Level Comparison of Qincun Reservoir

Figure 3 | Water level comparison chart for reservoirs during the 2019 flood season.

- Qiaoying Reservoir: Adjusted from 1,261.28 to 1,272.28 million m^3.
- Liaowan Reservoir: Adjusted from 576.20 to 681.90 million m^3.
- Changzhuo Reservoir: Adjusted from 6,893.00 to 6,916.60 million m^3.
- Nanshan Reservoir: Adjusted from 4,621.00 to 4,802.88 million m^3.
- Qinchuan Reservoir: Adjusted from 14,077.48 to 16,522.48 million m^3.

The flood discharge volumes for these reservoirs were also adjusted as follows:

- Qiaoying Reservoir: Adjusted from 0 to 0.
- Liaowan Reservoir: Adjusted from 148.70 million m^3 to 0.
- Changzhuo Reservoir: Adjusted from 1,234.30 million m^3 to 0.
- Nanshan Reservoir: Adjusted from 465.00 million m^3 to 0.
- Qinchuan Reservoir: Adjusted from 2,111.40 to 1,092.79 million m^3.

For detailed information, refer to Table 4.

The Sankey diagram of the regional reservoir group water resources' network joint adjustment in 2022 is shown in Figure 6.

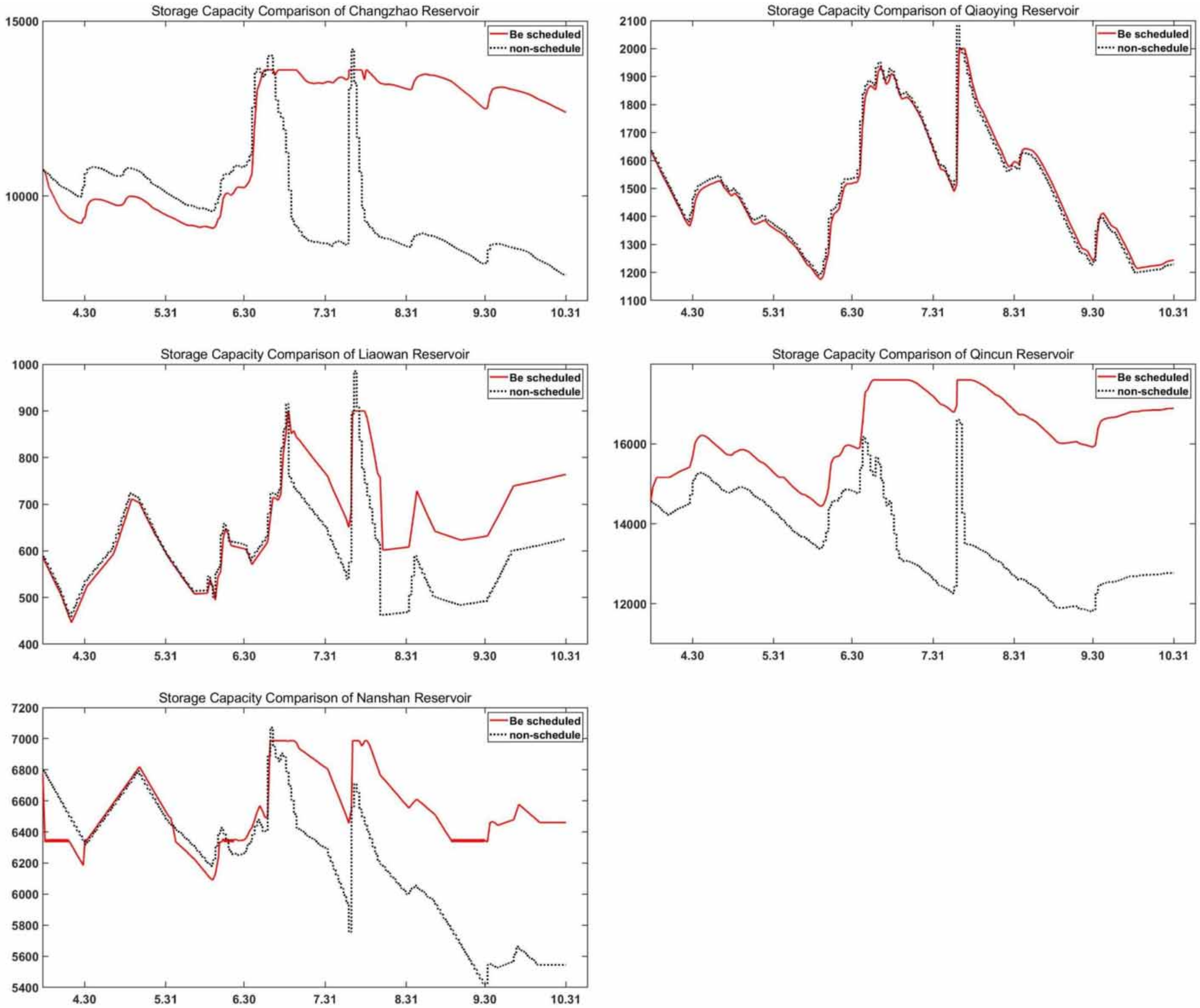


Figure 4 | Storage capacity comparison chart for reservoirs during the 2019 flood season.

By comparing the hydrological data of the five reservoirs before and after the simulated scheduling, it was observed that the total water storage increased by 2,767.18 million m^3, representing a 9.91% increase compared to conventional scheduling. Additionally, the total flood discharge volume decreased by 2,866.62 million m^3, resulting in a 72.40% reduction compared to conventional scheduling. This indicates a significant improvement in water resource utilization efficiency. The comparisons of water levels, water storage, and flood discharge volumes for each reservoir before and after the simulated scheduling are depicted in Figures 7–9.

3.3. Experimental result analysis

1. Comparison with conventional dispersed scheduling. In the years 2019 and 2022, which represent typical wet and normal water years, the simulated networked scheduling demonstrated significant advantages over conventional dispersed scheduling in terms of regional water resource management. In the two typical years, 24 and 19 scheduling operations were conducted, resulting in a total water transfer of 5,438.42 and 2,582.73 million m^3 for the reservoir group, respectively. Compared to conventional scheduling, the reservoir group's total water storage increased by 9,836.17 and 2,767.18 million m^3, representing an increase of 35.24 and 9.91% in water storage, respectively.
2. Comparison between typical years. In 2019, with the recorded precipitation of 2,025.3 mm, the water resource simulation with networked scheduling exhibited two peaks during the rainy season and the typhoon season. In contrast, in 2022, with a recorded precipitation of 1,515.5 mm, the water resource simulation with networked scheduling had only one peak

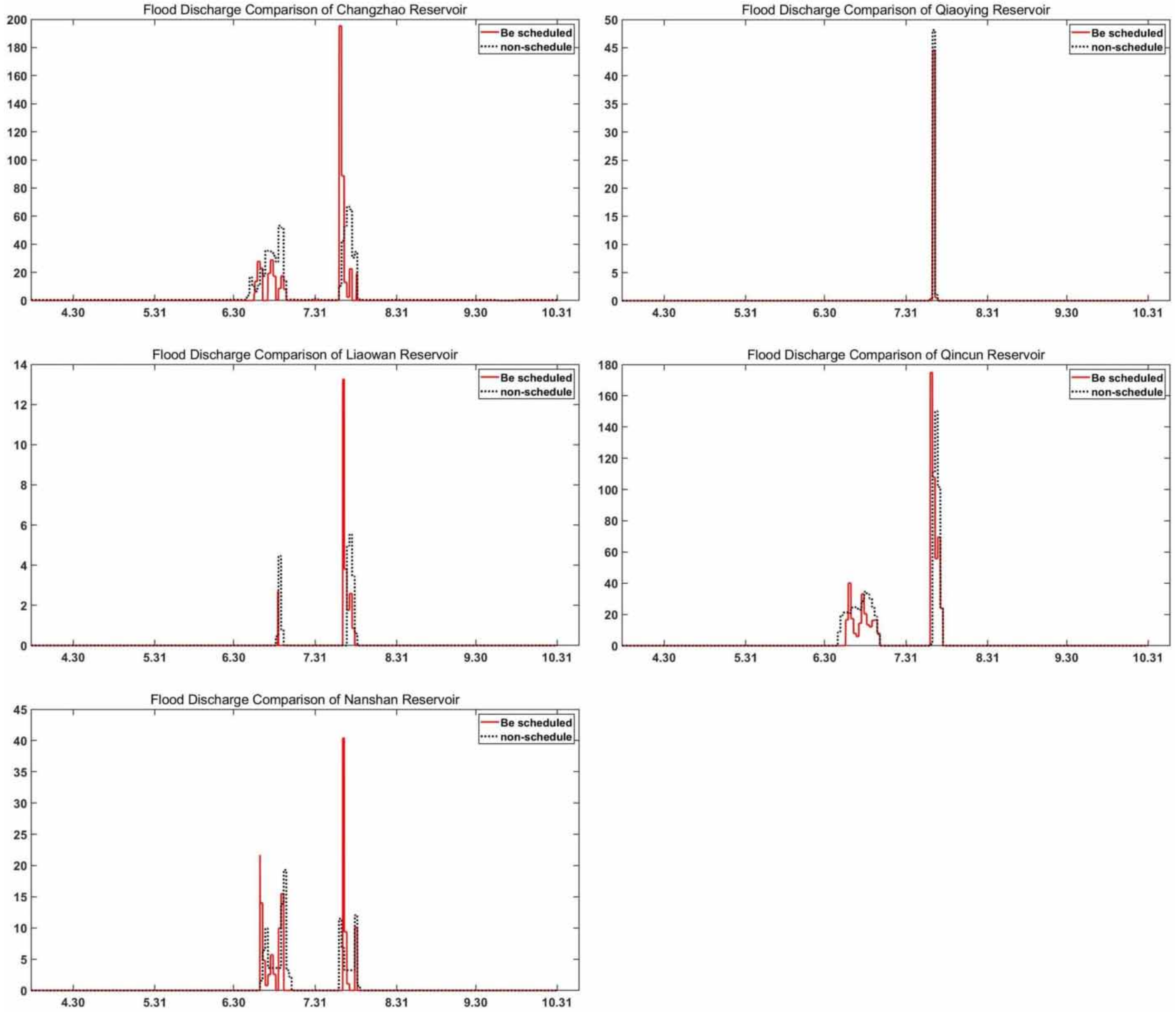


Figure 5 | Flood discharge comparison chart for reservoirs during the 2019 flood season.

Table 4 | Comparison of 2022 reservoir simulation scheduling data

Reservoir	**Initial state (April 15th)**		**Termination state – no scheduling (October 31st)**			**Termination state – with scheduling (October 31st)**			**Comparison before and after scheduling**	
	Water level	**Water volume**	**Water level**	**Water volume**	**Flood discharge volume**	**Water level**	**Water volume**	**Flood discharge volume**	**Water volume**	**Flood discharge volume**
Qiaoying	282.15	1,501.00	279.60	1,261.28	0	279.72	1,272.28	0	−11.00	0.00
Liaowan	144.23	630.80	142.30	576.20	148.70	145.85	681.90	0	−105.70	148.70
Changzhao	124.26	9,356.00	119.32	6,893.00	1,234.30	119.37	6,916.60	0	−23.60	1,234.30
Nanshan	119.72	6,334.00	112.56	4,621.00	465.00	113.37	4,802.88	0	−181.88	465.00
Qincun	94.43	14,705.84	93.62	14,077.48	2,111.40	96.66	16,522.48	1,092.79	−2,445.00	1,018.62
Total	/	/	/	27,428.96	3,959.40	/	30,196.14	1,092.79	−2,767.18	2,866.62

Note: In the table, the units are as follows: water level: meters (m); water volume: cubic meters (m^3); flood discharge volume: cubic meters (m^3).

Figure 6 | 2022 Sankey diagram showing the network's joint regulation of regional reservoir group water resources.

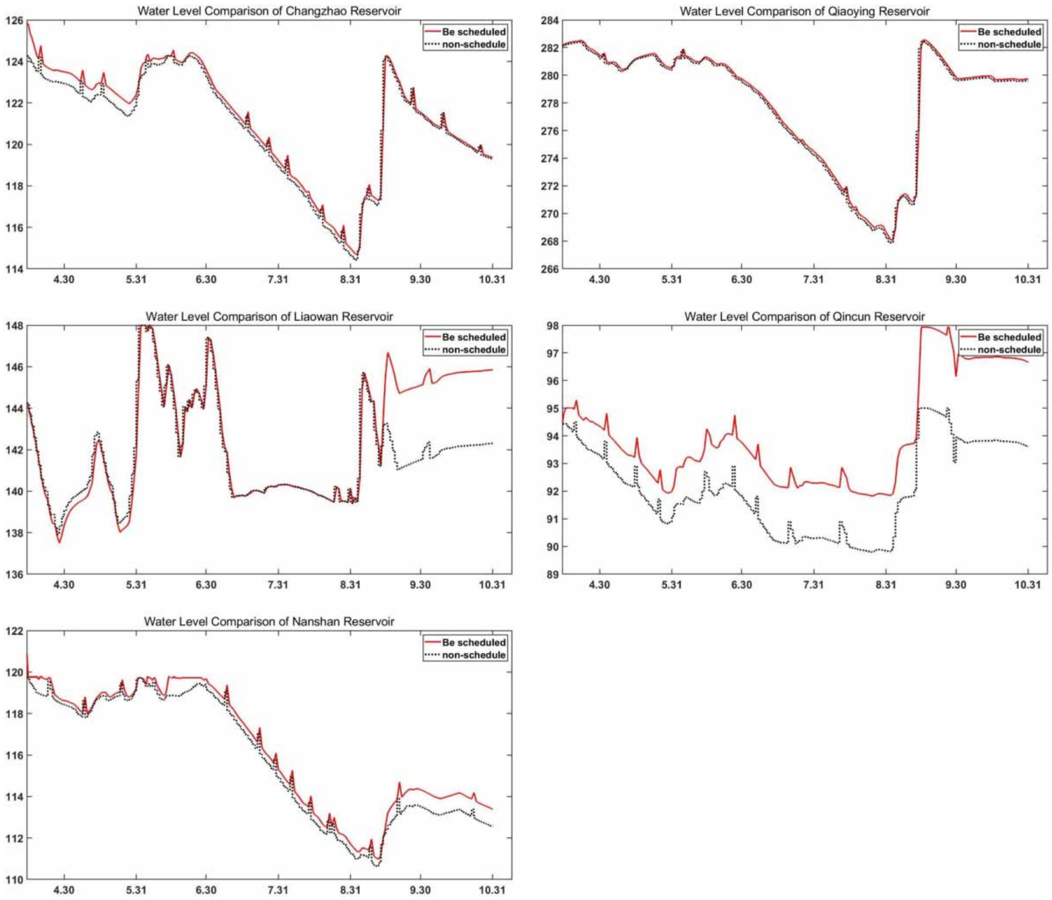


Figure 7 | Water level comparison chart for reservoirs during the 2022 flood season.

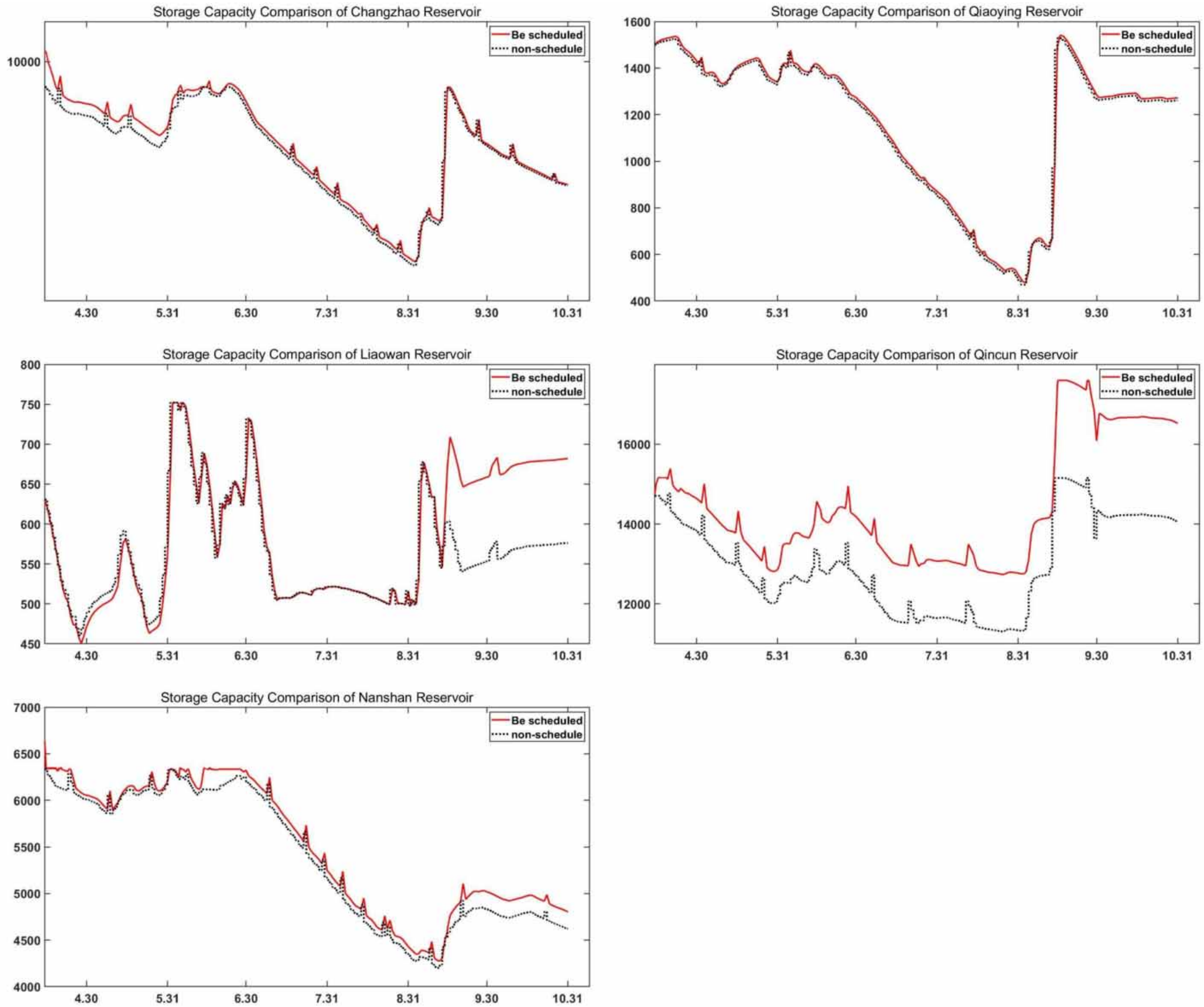


Figure 8 | Storage capacity comparison chart for reservoirs during the 2022 flood season.

during the typhoon season. Although the reservoir group increased water storage more in 2019 compared to 2022, the latter demonstrated better water resource utilization. In the two typical years, the total flood discharge volume decreased by 10,000.05 million m^3 (24.64%) in 2019 and by 2,866.62 million m^3 (72.40%) in 2022. The water increase in 2022, while smaller in quantity, was more valuable for drought resistance, as it mainly occurred during the water demand period.

4. RESEARCH CONCLUSIONS

The above simulated scheduling experimental research shows that the network flow model is effective in solving practical problems. The innovation of model research is mainly reflected in the following four aspects.:

1) The network flow model can effectively solve the problems of inefficient water utilization and unbalanced water allocation. Simulation experiments show that regional water resource networking and coordination based on the network flow theory can improve the efficiency of water resource utilization and solve the problem of unbalanced allocation among cities. The study shows that even the two cities of Xin-Sheng area, which are very close to each other, have an 'asynchronous rate' of water resources of 30% due to the differences in rainstorm patterns, reservoir resources, and industrial structures, which not only make the application of the network flow model very promising but also facilitate testing

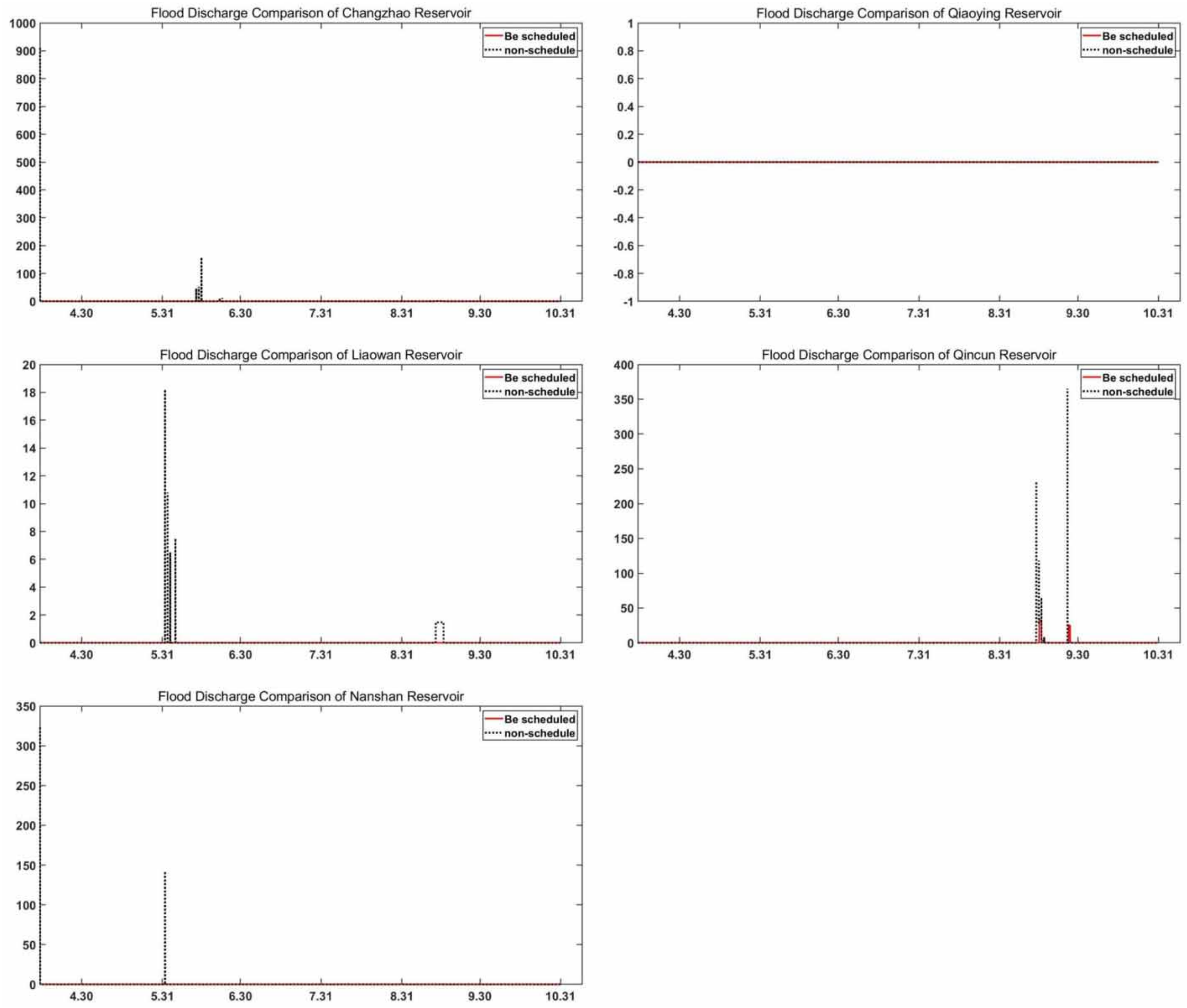


Figure 9 | Flood discharge comparison chart for reservoirs during the 2022 flood season.

for excessive water resources in the region. This 'asynchronous rate' is not only very promising for the application of network flow modeling but also can be used to test whether there is overexploitation of water resources in the region.

2) Scheduling in the year of abundant water is effective in improving the utilization of water resources, and scheduling in the year of dry water is effective in solving the problem of balanced water resources. In the case of the same rainfall in the dry water year, the annual rainfall process has a single peak, and the peak is in the typhoon period, which makes the scheduling more valuable in the dry water year with higher water resources under the incentive-compatible mechanism. In this case, compared with the current conventional dispatching of the Nanshan Reservoir, there will be a serious water shortage in the Xin-Sheng area, and the network flow model-based network dispatching will be more effective.
3) The incentive-compatible mechanism is the result of the combination of ancient water management ideas and modern science and technology. Its role is reflected in the regional administrative interests of the main body through the allocation of water resources to achieve unity and cooperation, mutual benefit, and a win-win situation to maximize regional interests. Secondly, the incentive compatibility is not only reflected in the compensation of economic benefits of water resource allocation but also in the construction of water ecological civilization, especially in the ecological restoration project of river and lake linkage.
4) Hydrodynamic conditions are a decisive factor in network flow modeling. The river system in the region is well developed, and the geographic conditions of each reservoir project are quite different, so through the network to form a network of

reservoir groups with many decentralized reservoirs in the region, the use of river hydrodynamic networking and joint regulation can not only improve the standard of maintaining the life and health of the river but also the hydrodynamic conditions of the river is an effective tool to test whether there is overexploitation of the real water resources.

Research shortcomings and prospects: This article mainly studies the network joint regulation scheme between regional reservoirs. Future research will further consider issues such as water supply from reservoirs to water plants and water supply from water plants to enterprises and residents.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Bachtiar, S., Limantara, L. M., Sholichin, M. & Soetopo, W. 2023 Optimization of integrated reservoir for supporting the raw water supply. *Civil Engineering Journal* **9** (4), 860–872.

Chen, X. 2019 Research on joint dispatching scheme of reservoir groups in regional water resources allocation. *Jianghuai Water Conservancy Science and Technology* **2**, 38–39.

Chen, M., Xu, Z., Cheng, L., Cheng, L., Hou, Q., Liu, P. & Qi, S. 2022 Exploring the influences of stream network structure and connectivity on water environment risk in China. *Water* **14** (24), 4007.

Deng, X. 2019 Correlations between water quality and the structure and connectivity of the river network in the Southern JiangSu Plain, Eastern China. *Science of the Total Environmental* **664**, 583–594.

Dibs, H., Jaber, H. S. & Al-Ansari, N. 2023 Multi-fusion algorithms for detecting land surface pattern changes using multi-high spatial resolution images and remote sensing analysis. *Emerging Science Journal* **7** (4), 1215–1231.

Dong, L., Xu, J. & Ma, R. 2016 Design and implementation of water resources optimization allocation system based on GIS network model. *Water Conservancy and Hydropower Technology* **47** (12), 7–12.

Dou, M., Song, S., Shi, Y. & Meng, J. 2022 Two-stage optimization of urban water system connection plan under structure-function coupling. *Progress in Water Science* **33** (1), 80–90.

Freeman, M., Pringle, C. & Jackson, C. 2007 Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources Association* **43** (1), 5–14.

Fu, Y-C., Xing, N-C., Zhao, J-Y., Zhang, S-P. & Zhang, J. 2017 Research on solutions to water shortage problems in water-scarce cities in the north – taking Langfang City as an example. *China Rural Water Conservancy and Hydropower* **11**, 1–5.

Jain, S., Singh, R. & Seth, S. 2000 Design flood estimation using GIS supported GIUHApproach. *Water Resources Management* **14**, 369–376.

Khalaf, N., Shareef, T. & Al-Mukhtar, M. 2023 Derivation of optimal two dimensional rule curve for dualistic reservoir water-Supply system. *Civil Engineering Journal* **9** (7), 1779–1794.

Li, H. 2010 Analysis of supply chain and water resources network configuration on the east route of the South-to-North Water Diversion Project. *People's Yellow River* **32** (5), 48–49.

Li, R., Chang, Y. & Wang, Z. 2021a Study of optimal allocation of water resources in Dujiangyan irrigation district of China based on an improved genetic algorithm. *Water Supply* **21** (6), 2989–2999.

Li, Z., Liu, C. & Hao, X. 2021b Theoretical foundation and priority areas of river and lake system connectivity. *Acta Geographica Sinica* **76** (3), 12.

Manoj, M. K. & Gupta, A. D. 2003 Application of Mike Basin for water management strategies in a watershed. *Water International* **28** (1), 27–35.

McKinney, D. C. & Cai, X. 2002 Linking GIS and water resources management models: An object-oriented method. *Environmental Modelling & Software* **17** (5), 413–425.

Pringle, C. 2003 What is hydrologic connectivity and why is it ecologically important?. *Hydrological Processes* **17** (13), 2685–2689.

Sarker, S., Veremyev, A., Boginski, V. & Singh, A. 2019 Critical nodes in river networks. *Scientific Reports* **9** (1), 11178.

Schmadel, N. M., Harvey, J. W., Alexander, R. B., Schwarz, G. E., Moore, R. B., Eng, K., Gomez-Velez, J. D., Boyer, E. W. & Scott, D. 2018 Thresholds of lake and reservoir connectivity in river networks control nitrogen removal. *Nature Communications* **9** (1), 2779.

Wohl, E. 2017 Connectivity in rivers. *Progress in Physical Geography* **41** (3), 345–362.

Wu, X. & Wang, Z. 2022 Multi-objective optimal allocation of regional water resources based on slime mould algorithm. *The Journal of Supercomputing* **78** (16), 18288–18317.

Xiao, L., Ju, W. Sun, B., Hu, Z., Gao, X,, Zhang, J. & Zhao, J. 2022 Evaluation of plain urban river network connectivity based on AHP-entropy weight method – taking Langfang City as an example. *South-to-North Water Diversion and Water Conservancy Science and Technology (Chinese and English)* **20** (2), 352–364.

Yao, Z., Wang, Z., Cui, X. & Zhao, H. 2023 Research on multi-objective optimal allocation of regional water resources based on improved sparrow search algorithm. *Journal of Hydroinformatics* **25** (4), 1413–1437.

Yu, Z., Wang, Q., Xu, Y., Lu, M., Lin, Z. & Gao, B. 2022 Dynamic impacts of changes in river structure and connectivity on water quality under urbanization in the Yangtze River Delta plain. *Ecological Indicators* **135**, 108582.

Zhou, K. 2021 Research on optimal allocation of water resources in Zhengzhou City based on red line management. *People's Yangtze River* **52** (4), 124–129.

Zuo, Q. & Cui, G. 2020 Assessment of the impact of human activities on the connectivity of rivers and lakes. *Acta Geographica Sinica* **75** (7), 11.

First received 8 December 2023; accepted in revised form 25 January 2024. Available online 7 February 2024