Joint optimal operation of the South-to-North Water Diversion Project considering the evenness of water deficit

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Abstract. Inter-basin water transfer project is the main measure to address the water deficit crisis caused by uneven distribution of water resources. The current water transfer operation mainly tends to be present in areas with small water transfer costs and is prone to encounter the problem of spatial and temporal imbalances in water allocation. To address these issues, this paper defines a Water Deficit Evenness Index (WDEI) aimed at minimizing regional differences in water scarcity and sharing the pressure of water scarcity as a social demand objective. This index is incorporated into a joint optimization model for the Jiangsu Section of the South-to-North Water Diversion project (J-SNWDP), which comprises both the ecological objective of the total water deficit (TWD) and the economic objective of the pumping water (PW). Further, the Nondominated Sorting Genetic Algorithm III (NSGA-III) and multi-attribute decision-making were applied to solve the model and obtain an optimal operation strategy. The results showed that: (1) The WDEI defined in this paper can mitigate the synchronized water scarcity in certain water users. In typical normal years (wet year and dry year), the WDEI shows a reduction of 94.2% (81.8%, 76.7%) compared to the historical operation strategy; (2) The optimized operation strategy can significantly reduce TWD and PW by 82.06% (37.69%, 52.36%) and 45.13% (3.25%, 21.51%) compared with the historical values, respectively, which can improve the water supply satisfaction and reduce the project cost. At the same time, the lake storage capacity of the optimal operation strategy performs well, and the water transfer efficiency of the river is significantly improved; (3) In this paper, targeted optimal operation strategies and potential ways to secure the project tasks are proposed for different natural flow. Overall, it is of great significance to study the water supply equity in the J-SNWDP to alleviate the concentrated water deficit in Jiangsu Province and other similar regions.

Key Words. South to North Water Diversion Project; Water deficit Evenness index; multi-objective optimization; NSGA-III; Multi-attribute decision-making.

1 Introduction

Influenced by the impacts of global climate change, human activities, and increasing water demand, issues like regional water resource deficits, flood and drought disasters, and the conflicts between water supply and demand are progressively intensifying (Florke et al., 2018; Ma et al., 2020; Kato and Endo, 2017; Rossi and Peres, 2023). These social issues have become one of the key factors constraining regional and even global sustainable development and environmental protection (Li et al., 2020; Liu et al., 2021; Tian and Destech Publicat, 2017). Inter-basin Water transfer (IBWT) projects have been widely constructed worldwide as an effective way to address water deficit issues caused by uneven distribution of water resources, and improve their utilization efficiency (Sun et al., 2021; Wei et al., 2022; Medeiros and Sivapalan, 2020). At least 10 % of the cities worldwide receive water from IBWT projects (Mcdonald et al., 2014). The birth of the Lancang-Mekong Cooperation promotes the joint development of six countries, namely China, Cambodia, Laos, Myanmar, Thailand and Vietnam (Ghoreishi et al., 2023). The California State Water Project, the Colorado River Aqueduct (Lopez, 2018), the Senqu-Vaal transfer in South Africa and Lesotho (Gupta and Van Der Zaag, 2008), the Snowy Mountains Scheme in southeastern Australia (Pigram, 2000), and other inter-basin water transfer projects have all effectively alleviated water scarcity issues in various regions (Lu et al., 2021). The South-to North Water Diversion Project (SNWDP) in China (Guo and Li, 2012) is considered the largest inter-basin water transfer project in the world. The project runs along numerous water users, and the water resources it provides have already benefited hundreds of millions of people, with even more expected to be served in the future (Pohlner, 2016).

There are considerable studies on the water resources operating strategy of the supply-oriented IBWT projects in terms of social, economic, ecological, and environmental (Gan et al., 2011; Zhu et al., 2014; Liu and Zheng, 2002; Xu et al., 2013). In general, meeting the water demand of various users is the main task of the IBWT project, with the consideration of minimizing water deficit in previous studies (Guo et al., 2020; Wang et al., 2008). Rather than the total amount of water deficit, the crux of the problem may actually be the concentration of water deficit in a certain period of time or region, which has not yet received sufficient attention and remains a major challenge. Therefore, both the total and spatial-temporal distribution of water deficit should be considered in the optimization process (Xu et al., 2013). In addition, users' demands and decision makers' benefits should be considered as priorities (Zhang et al., 2012), so minimizing pumped water (PW) is a direct way to reduce costs. At the same time, the proportion of the amount of abandoned water and the water withdrawn from the river in the process of water diversion should be taken as secondary considerations (Guo et al., 2018). However, due to the data on natural water and user water demand as the determining factors of the operation strategy, and the obvious regional differences, most of the objectives determined by the existing studies can only solve small-scale projects.

As the project continues to operate, the focus of research should be concentrated on the planning of operational strategies to sustain the long-term operation of the project and enhance its comprehensive benefits. For IBWT projects, due to regional differences, improving operational efficiency and benefits while ensuring water supply is a challenging task. Currently, most IBWT projects primarily adhere to various laws and policies established by the government. These projects comply with annual water demand plans submitted by sectors like agriculture, domestic use, and ecology. The water supply principle is based on 'prioritizing users that are closer in distance, have lower water supply costs, and have larger water demands' to develop operation strategies. Such method of water diversion results in lower satisfaction levels for users that are farther in distance and have higher costs, leading to an imbalance in water supply and causing some users to face significant pressure from concentrated water deficits. Furthermore, these projects lack annual predictive assessments of local hydrological conditions and fail to develop targeted operational strategies for diverse natural inflows or extreme events. Developing operational strategies without considering the evenness of water deficit and natural inflows is unscientific. This inspires the primary objective of optimization in this paper.

The South-to-North Water Diversion Project (SNWDP) presents a highly complex and dynamic water situation, especially in the Jiangsu section (Vogel et al., 2015). Due to differences in the location and timing of natural inflows and water users, and the aforementioned issues in operational strategies, an imbalance in water supply has arisen. At present, there have been some studies attempting to address this issue, but they tend to focus on meeting the total water demand and improving the overall benefits (Li et al., 2017; Zhuan et al., 2016), neglecting the fairness of water supply among different regions. Water supply may become concentrated on a specific user or time period. Therefore, it is of great theoretical significance and practical application value to optimize the existing operation strategy to alleviate the concentration of water deficit so as to realize the comprehensive benefits of the IBWT project (Nazemi and Wheater, 2015; Peng et al., 2015).

To address the above problem, this paper studies the Jiangsu section of South-to-North Water Diversion project (J-SNWDP). The three main contributions of this paper are as follows: (1) The definition of the Water Deficit Evenness Index (WDEI) and its incorporation into the joint optimal operation model of the J-SNWDP, along with the Total Water Deficit (TWD) and the Pumped Water (PW), aim to satisfy the requirements of both decision-makers and users; (2) The incorporation of the amount of abandoned water and the water withdrawn from the Yangtze River into the decision indicator set, along with the application of the multi-attribute decision making method for filtering the Pareto front strategies of NSGA-III, results in the identification of the optimal operation strategy that balances economic and ecological benefits; (3) The comparison of the optimal operation strategy selected in three typical years (wet, normal, and dry) with the historical operation strategy under identical natural conditions in the paper serves to verify the superiority of the optimization results, offering reasonable optimization suggestions for the J-SNWDP and other similar regions.

2 Materials and methods

2.1 Study area and data

2.1.1 Regional Overview

The Jiangsu section of the South-to-North Water Diversion Project (J-SNWDP) crosses the Yangtze River and Huai River basins. The simplified map of the J-SNWDP is shown in Fig. 1. The Beijing-Hangzhou Grand Canal runs through the north and south of Jiangsu Province, connecting the Yangtze River basin, the Huai River basin and the Yishusi River basin. The total length of the Jiangsu section is 404 km, along which six cities are involved, namely Yangzhou, Huaian, Yancheng, Suqian, Lianyungang and Xuzhou. The J-SNWDP consists of 3 impounded lakes (Hongze Lake, Luoma Lake, Nansi Lake), 6 sluices (e.g., Erhe sluice, Gaoliangjian sluice, etc.), and 13 pumping stations (Huaian Station, Jiangdu Station, etc.), forming a double-route water diversion system including the West Canal Route and the East Canal Route. The water supply scope of the whole J-SNWDP covers three provinces of Jiangsu, Anhui, and Shandong, supplementing the agricultural, industrial and domestic water supply as well as navigation and ecological water supply in the areas along the water transfer route. The scale parameters of the pumping stations and sluices in J-SNWDP are listed in Table 1. The characteristics of the lakes in the J-SNWDP are shown in Table 2.

Table 1: Pumping stations and sluices of the Jiangsu section of the South-to-North Water Diversion Project

	Number	name	Scale (m^3/s)	Number	name	Scale (m^3/s)
Pumping station	P1	Jiangdu	100	P8	Sihong	120
	P2	Baoying	400	P9	Suining	110
	P3	Jinhu	400	P10	Zaohe	175
	P4	Huaian	300	P11	Pizhou	110
	P5	Hongze	150	P12	Liushan	125
	P6	Huaiyin	300	P13	Taierzhuang	125
	P7	Siyang	230			
Sluice	S1	Nanyunxi	400	S4	Yangzhuang	500
	S2	Gaoliangjian	500	S5	Yanhe	500
	S3	Erhe	500	S6	Huaiyin	500

Table 2: Lakes of the Jiangsu section of the South-to-North Water Diversion Project

Lake name		Hongze	Luoma	Nansi
Dead lake level (m)		11.30	21.00	31.30
Normal lake level (m)	Flood season	12.50	22.50	32.30
	Non-Flood season	13.50	23.00	32.80
Regulation storage (10^8 m^3)	Flood season	15.30	4.30	4.94
	Non-Flood season	31.35	5.90	8.00
Monthly range lake level for water diversion (m)	Jul - Aug	12.00	22.22-22.10	31.80
	Sep - Oct	12.00-11.90	22.10-22.20	31.50-31.90
	Nov - Mar	12.00-12.50	22.10-23.00	31.90-32.80
	Apr - Jun	12.50-12.00	23.00-22.50	32.30-31.80

When the J-SNWDP is supplying water along the water transfer route, users closer to the water source (such as JBHD User, S-S User, LM User, etc.) are generally prioritized. On the other hand, users like the Feihuanghe User, Lianyungang User, and

Siyang-Zaohe User, which are located farther from the water source and receive less water from Luoma Lake, often require water to be pumped from the Yangtze River and Hongze Lake for replenishment. Combined with the uneven spatial and temporal distribution of precipitation, these recipient zones are more susceptible to water deficits.

In Fig. 2, the complex relationship of the J-SNWDP is generalized into a schematic diagram according to the geographical location. In order to represent the main components of the system and the connection between the backbone rivers, we regard lakes, pumping stations, sluices as the nodes and the backbone river as the connecting line, while the water users are reasonably distributed among the nodes of the water transmission route.

The joint operation process of the J-SNWDP is described as follows. In addition to natural precipitation and lake inflow, the Yangtze River is the main water source of water, which is pumped from the river to the West Route and the Canal Route by P1 pumping station. The West Route is pumped step by step from P2, P3, and P4 to Hongze Lake through Sanyang River, and Jinbao Channel, and pumped from P9, P10, and P11 to the north through Xuhong and Fangting Rivers. The Canal Route along the Beijing-Hangzhou Grand Canal route is pumped north from P5, P6, P7, and P8. The two water transmission routes supplement the water demand of users along the routes while pumping to the north, and merge into one line at the intersection of Fangting River and Zhongyun River. It is then pumped further north until P12 and P13 are transported to Nansi Lake via Bulao and Hanzhuangyun Rivers, respectively, thus delivering water outside the Jiangsu province. When the natural inflow is high, the Hongze Lake can be discharged via P1 on the West Route, or through S2, S3, S4, S5, and S6 to the relevant rivers and users. Luoma and Nansi Lakes are discharged through the original water transmission routes.

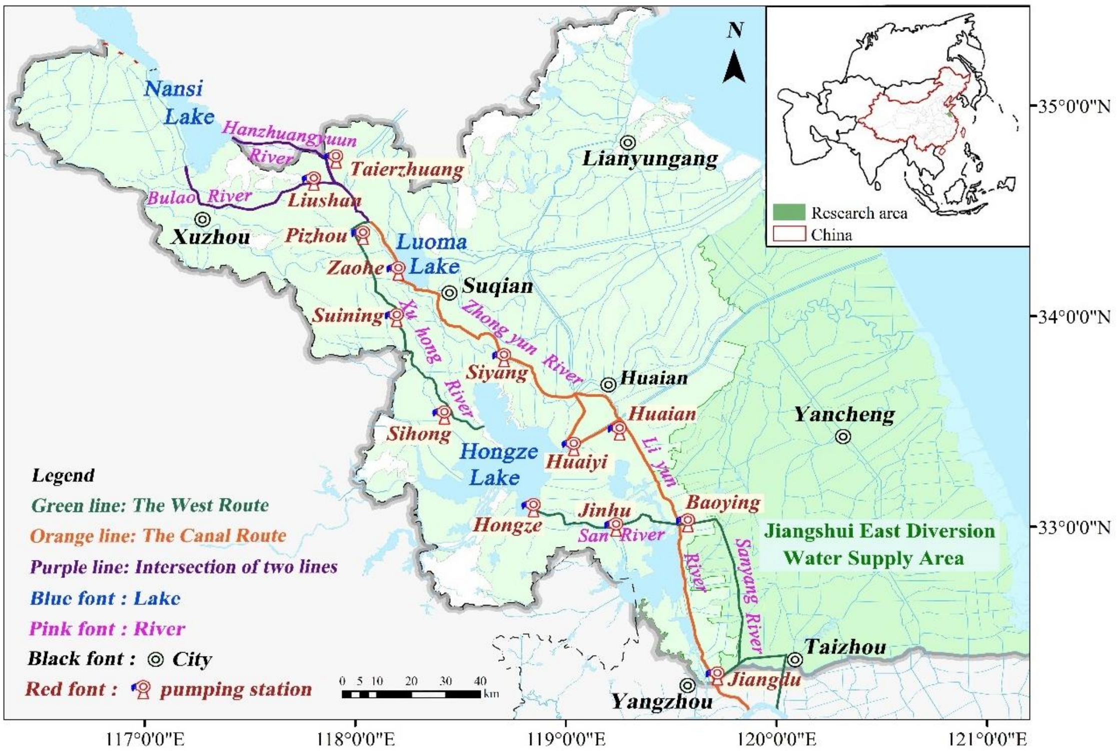

Figure 1: The Jiangsu section of the South-to-North Water Diversion Project (J-SNWDP). The orange, green and purple lines represent the Canal Route, the West Route, and their intersection to transport water outside the province, respectively.

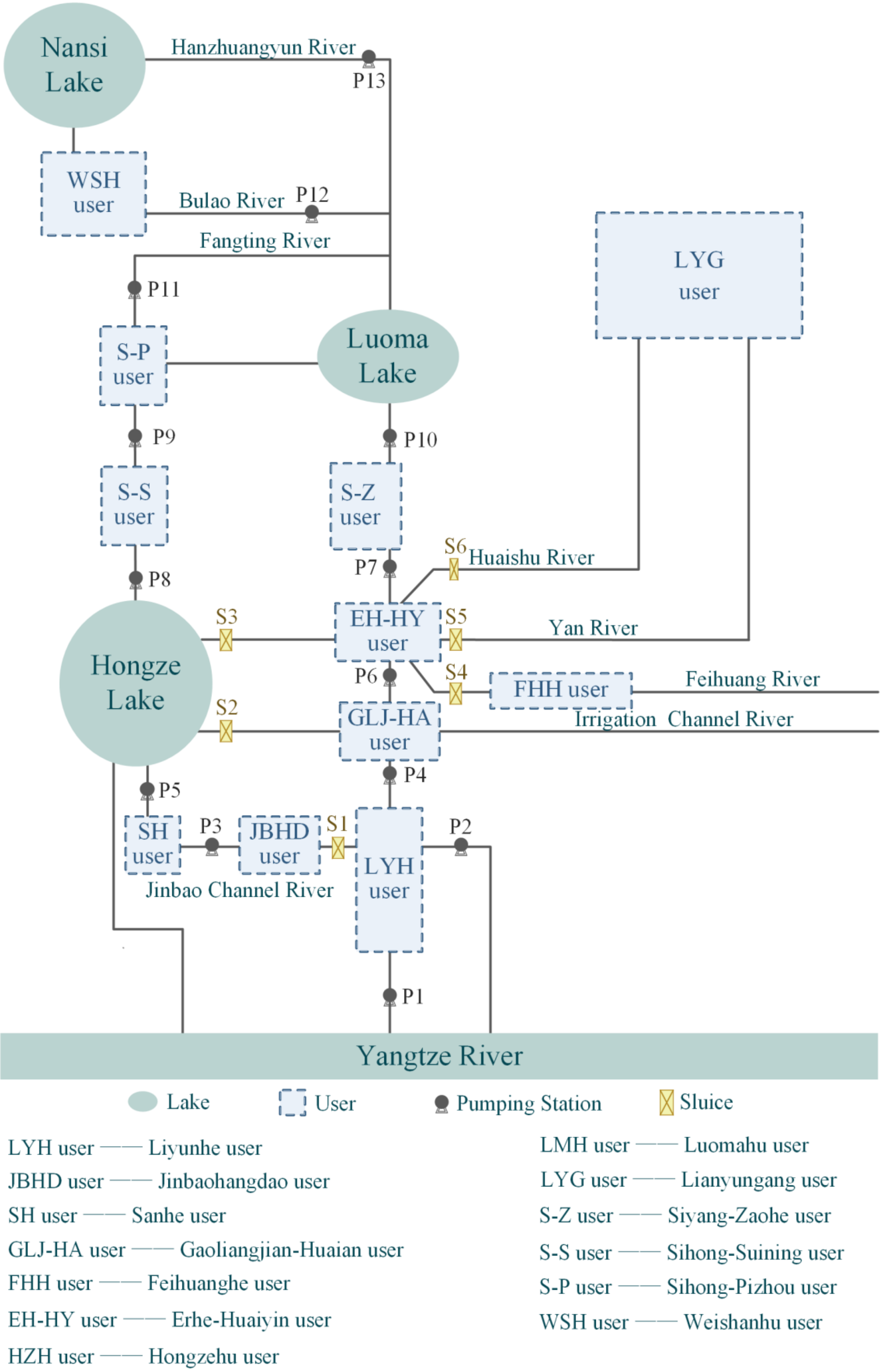

Figure 2: Schematic diagram of the Jiangsu section of the South-to-North Water Diversion Project (J-SNWDP).

2.1.2 Data

The joint optimal operating model of the J-SNWDP uses a monthly time step. According to the annual natural inflow data of

Hongze (HZ), Luoma (LM) and Nansi (NS) Lake since 2013 from Jiangsu Water Resources Bulletin, three hydrological years were selected to represent wet (2017.10-2018.09, annual mean inflow: 465.12 × 10^8 m^3), normal (2019.10-2020.09, annual mean inflow: 172.80 × 10^8 m^3), and dry (2013.10-2014.09, annual mean inflow: 103.06 × 10^8 m^3) years, respectively. The typical annual runoff curves of HZ, LM and NS Lakes are shown in Fig. 3. The water supply area of the J-SNWDP is divided into 13 receiving areas according to geographical location, and water demand data is provided by the Jiangsu Provincial Water Resources Department: wet years (2017.10-2018.09, water demand: 171.29 × 10^8 m^3), normal years (2019.10-2020.09, water demand: 173.51 × 10^8 m^3), normal years (2013.10-2014.09, water demand: 181.75 × 10^8 m^3).

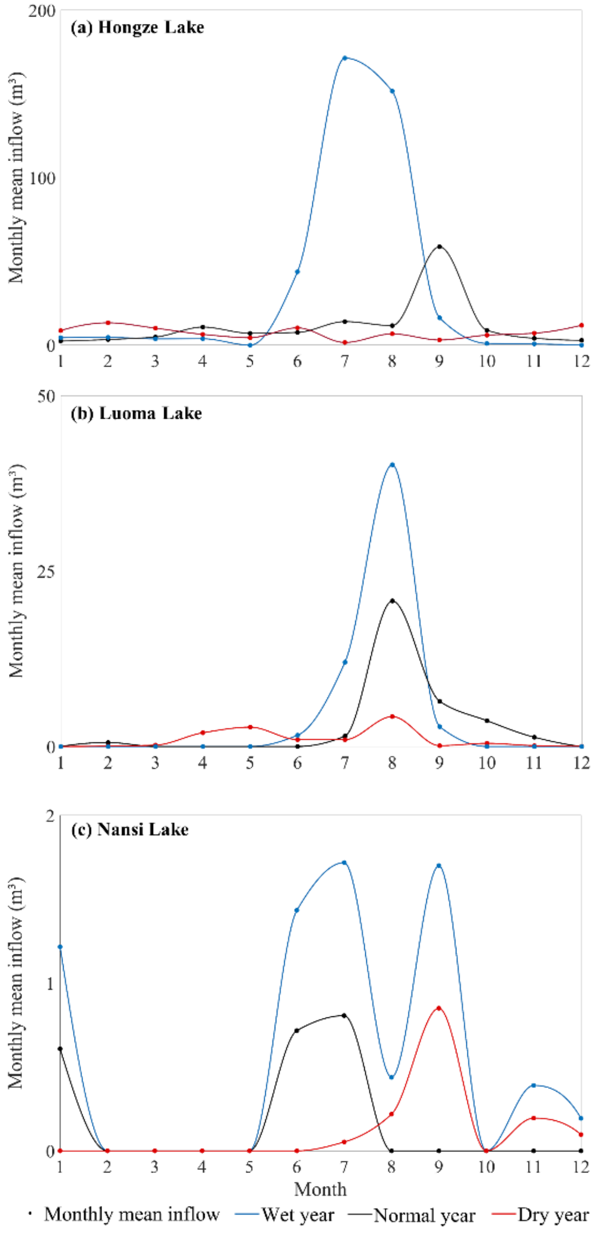

Figure 3: Monthly mean inflow curves of the (a) Hongze, (b) Luoma, and (c) Nansi lakes in typical wet, normal, and dry years.

2.2 Water deficit evenness index

For IBWT projects, issues of equitable water supply often arise, especially for projects like the J-SNWDP, which has 13 water users along its route. Different users have significant spatial variations in location, as well as large differences in water supply costs. Consequently, the concentration of water deficits is particularly severe when there are multiple users, which results in some of them being stressed by water deficits.

Luoma Lake, which almost receives no inflow during dry periods yet bears the primary responsibility for out-of-province water supply task, requires multilevel pumping stations to pump water upward (water needs to be pumped from Luoma Lake through two pumping stations, from Hongze Lake through six pumping stations, and from the Yangtze River through nine pumping stations), creating a substantial burden on water supply. In past water supply dispatching of the J-SNWDP, the pursuit of maximum benefit while neglecting this issue would obviously cause certain users to bear severe water deficit risks, resulting in significant damage to the water supply system.

Therefore, considering the fairness of water supply is very important for the practical operation of the project. In this paper, the WDEI (Water Deficit Evenness Index) is defined as an indicator representing the degree of water deficit concentration, and the variance van reflect the difference in water deficits among various recipient zones. By incorporating the WDEI index into the optimization objective and minimizing it, the difference in water deficit can be reduced as much as possible. So the WDEI is below：

$$WDEI=\frac{\sum_{t=1}^{n}(QR(i,t)-\frac{\sum_{i=1}^{n}QR(i,t)}{n})^2}{n}, \tag{1}$$

where $QR(i, t)$ is the water deficit of the i th user at time step t，i= 1, 2, …, n, with n being the total number of users (n= 13 in this study), t= 1, 2, …, T, with T being the whole operating period.

2.3 The joint optimal operation model of J-SNWDP

Herein, the joint optimal operating model of the J-SNWDP was constructed with 228 decision variables (13 pumping stations and 6 sluices). The objective function and associated constraints are formulated as follows.

2.3.1 Objectives

(1) Minimizing the total water deficit (TWD)

TWD is a measure of how well the operation strategy completion is being implemented. This objective aims to minimize the total amount of water deficit at the end of a given operation period, potentially improving the satisfaction of water demand for users and increasing the operation strategy completion.

$$TWD=\min\sum_{t=1}^{T}\sum_{i=1}^{n}QR(i,t), \tag{2}$$

where $QR(i, t)$ is the water deficit of the i th user at time step t，i= 1, 2, …, n, with n being the total number of users (n= 13 in this study), t= 1, 2, …, T, with T being the whole operating period.

(2) Minimizing water deficit evenness index (WDEI)

WDEI indicates the degree of concentration of the water deficit and can be used as an indicator of the uniformity of water diversion. The lower the WDEI, the better the strategy is.

$$WDEI = \min \frac{\sum_{t=1}^{n} \left(QR(i,t) - \frac{\sum_{i=1}^{n} QR(i,t)}{n}\right)^2}{n}, \tag{3}$$

where $QR(i, t)$ is the water deficit of the i th user at time step t，i= 1, 2, …, n, with n being the total number of users (n= 13 in this study), t= 1, 2, …, T, with T being the whole operating period.

(3) Minimizing pumped water (PW)

PW reflects the economy of operation strategy. The lower the PW is, the less the operating costs.

$$PW = \min \sum_{t=1}^{T} \sum_{p=1}^{P} QS(p,t), \tag{4}$$

where $QS(p, t)$ is the water pumped by the p th pumping station at time step t, p= 1, 2, …, P, with P is the total number of pumping stations (P= 13 in this study).

2.3.2 Constraints

Systems operation should obey operating rules and physical constraints, such as water balance, pumping capacity, and lake storage constraints. The mathematical expressions of the constraints are shown as below.

(1) Water balance constraint

The water balance constraint should be satisfied in the water diversion process.

$$V(i, t+1) = V(i, t) + Q(i, t) + DI(i, t) + PC(i+1, t) - DO(i, t) - W_1(i, t) - PR(i, t), \tag{5}$$

At time step t, where $V(i, t)$ is the water storage of the i th lake at time step t; $Q(i, t)$ is the inflow of the i th lake; $W_1(i, t)$ is the water demand of the i th lake (water to be supplemented by J-SNWDP after deducting the locally available water); $DO(i, t)$ is water diversion to the north from the i th lake; $DI(i, t)$ is the water pumped into the i th lake; $PC(i, t)$ is the water discharged into the i th lake; $PR(i, t)$ is the water discharged from the i th lake.

(2) Pumping capacity constraint

$$\begin{aligned} &0 \le DO(i, t) \le DO_{max}(i, t) \\ &0 \le DI(i, t) \le DI_{max}(i, t) \quad , \end{aligned} \tag{6}$$

At time step t, where $DO(i, t)$ is water diversion to the north from the i th lake; $DI(i, t)$ is the water pumped into the i th lake; $DO_{max}(i, t)$ is the maximum pumping capacity that is pumped into the i th lake; $DI_{max}(i, t)$ is the maximum pumping capacity that is diverted north from the i th lake.

(3) Sluice capacity constraint

$$0 \le PR(i, t) \le PR_{max}(i, t), \tag{7}$$

where $PR(i, t)$ is the water discharged from the i th lake; $PR_{max}(i, t)$ is the maximum sluice capacity at time step t.

(4) Lake storage constraint

$$V_{min}(i, t) \le V(i, t) \le V_{max}(i, t), \tag{8}$$

where $V(i, t)$ *is* the water storage of the i th lake at time step t; $V_{min}(i, t)$ and $V_{max}(i, t)$ are the minimum and maximum water storage capacities at time step t, respectively. When $V(i,t) < V_{\min}(i,t)$ is water deficit, $QR(i,t) = V_{\min}(i,t) - V(i,t)$, ensure that the lake level is above the limit level; when $V(i,t) > V_{\max}(i,t)$ is abandoned water, ensure that the water storage of the lakes is within a reasonable range.

(5) Minimum lake levels for water diversion

$$Z_{min}(i, t) \le Z(i, t) \le Z_{max}(i, t), \tag{8}$$

where $Z(i, t)$ is the level of the i th lake at time step t; $Z_{min}(i, t)$ and $Z_{max}(i, t)$ are the minimum and maximum level of the i th lake at time step t, respectively.

2.4 Model solving and solution selection

Fig.4 shows the optimization method and process of the Jiangsu section of the South-to-North Water Diversion Project. Considering the complex objectives and various physical constraints, the NSGA-III algorithm (Deb and Jain, 2014) is used in this paper to solve the model in this paper. NSGA-III has been widely used to solve various water-resource optimal diversion problems and to obtain optimal operation strategies with the advantages of fast execution speed and high efficiency (Ni et al., 2019; Tang et al., 2021; Zhou et al., 2020). The NSGA-III is used to solve the joint optimal operation model of the J-SNWDP under three typical conditions: wet year, normal year and dry year. The model takes the actual value of the pumped water of each pumping station as the decision variable. The population size, generation, crossover rate and mutation rate are set to 200, 20000, 0.9 and 0.1, respectively. The application of NSGA-III to the model can be summarized as the following steps：(1) Take 12 monthly water pumped of a year as the decision variables and initializes the population of size N based on the physical constraints of operation; (2) Calculate the objectives of TWD, EWD and WP for each chromosome and sort by Nondominated strategy; (3) Select excellent chromosome from population non-dominated as parent chromosome and create child chromosome by the cross and mutation operation. (4) Combine the parent chromosome with the child chromosome and update the population by Nondominated strategy. (5) Repeat the four steps above until the number of iterations is reached.

After solving the model using NSGA-III, we obtained a set of optimized running strategies (i.e., strategies based on the Pareto-ranked top 200). In order to measure the operation effect more comprehensively, more indicators are needed to assist in selecting an optimal operation strategy. Therefore, this paper further applies multi-attribute decision-making methods to screen and determine the optimal operation strategy. The abandoned water reflects the regulation and storage capacity of the lakes, and the water withdrawn from the Yangtze River reflects the impact of the water transferred outside the system on the operation strategy. A multi-attribute decision indicator set is constructed, which included five optimization objectives for the total water deficit, the water deficit evenness index, the pumping water, the abandoned water and the water withdrawn from the Yangtze River. Indicators are divided into water use efficiency and cost of water use indicators as shown in Fig. 4. In this paper, we adopt the Analytic Hierarchy Process (AHP) method to determine the subjective weights and the entropy weighting method to determine the objective weights, further the combination weights are obtained by linear weighted average.

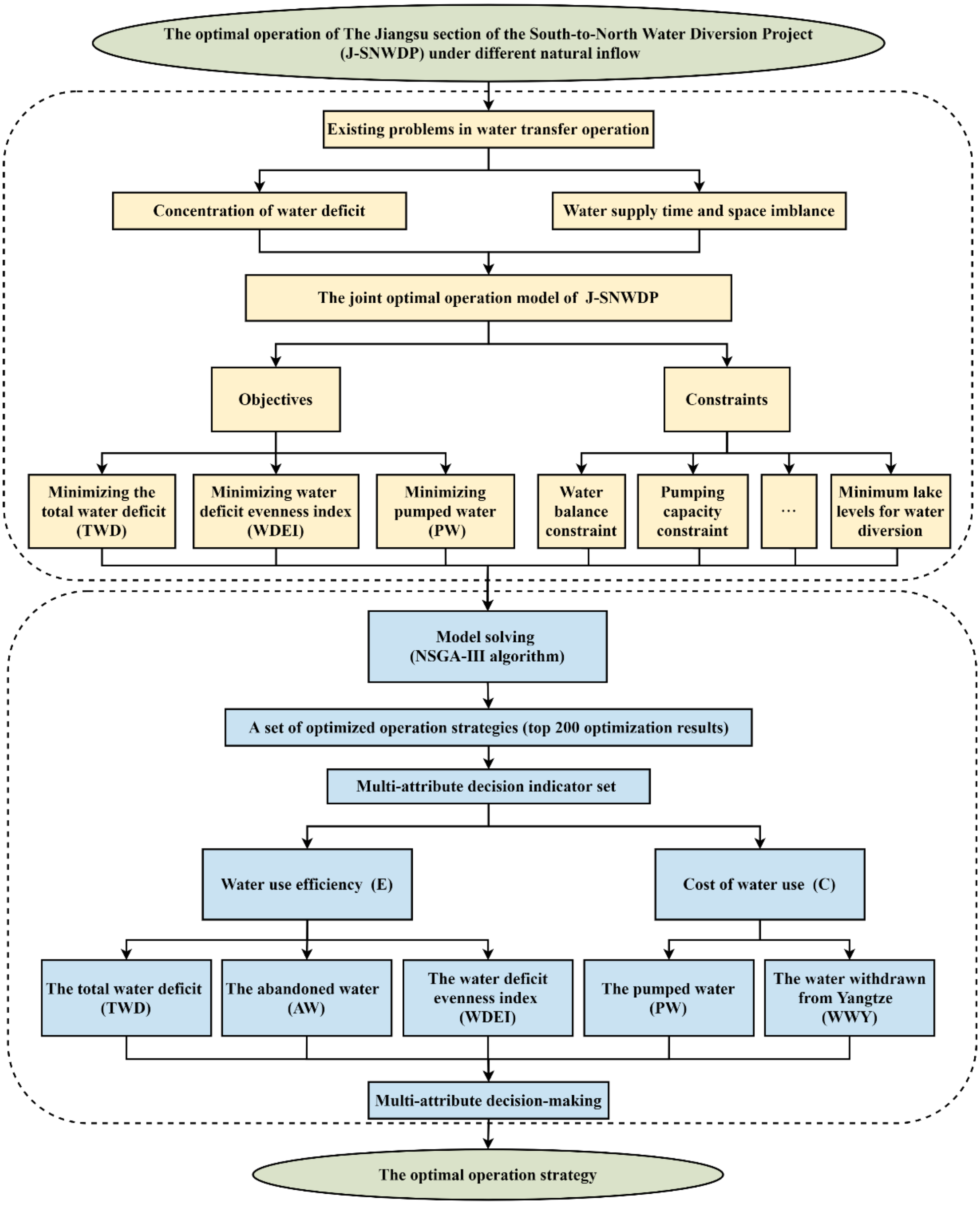

Figure 4: Optimization process of the Jiangsu section of the South-to-North Water Diversion Project (J-SNWDP).

3 Results

3.1 Pareto front strategies of NSGA-III under different years

The historical operation strategy of the J-SNWDP follows the principle of 'replenishing the lake during water deficit, and discharging during water surplus', with the primary goal of ensuring the completion of water supply tasks. Firstly, the simulation of a single lake is carried out, and then the simulation of each storage lake is carried out according to the top-down order, so as to complete the conventional operation of the engineering system. Such a method is simply "robbing Peter to pay Paul". The external water transfer is not fully deployed, but increases the operating costs. In contrast, the joint optimal operation exhibits several advantages, such as controlling the minimum WDEI of each user, ensuring that even if the total water deficit and the historical operating strategy are the same, the water deficit pressure is evenly distributed to avoid undesirable water deficit concentration. In addition, the optimal operation process pays more attention to the water storage function of the lake. In the non-flood season, the water level of the reservoir is kept at the normal water storage level as much as possible, and the water storage (discharge) is appropriate according to different natural inflow, so that the whole system can realize the lake storage in the flood season and non-flood season at the same time, and improve the utilization rate of water resources while fulfilling the water supply task.

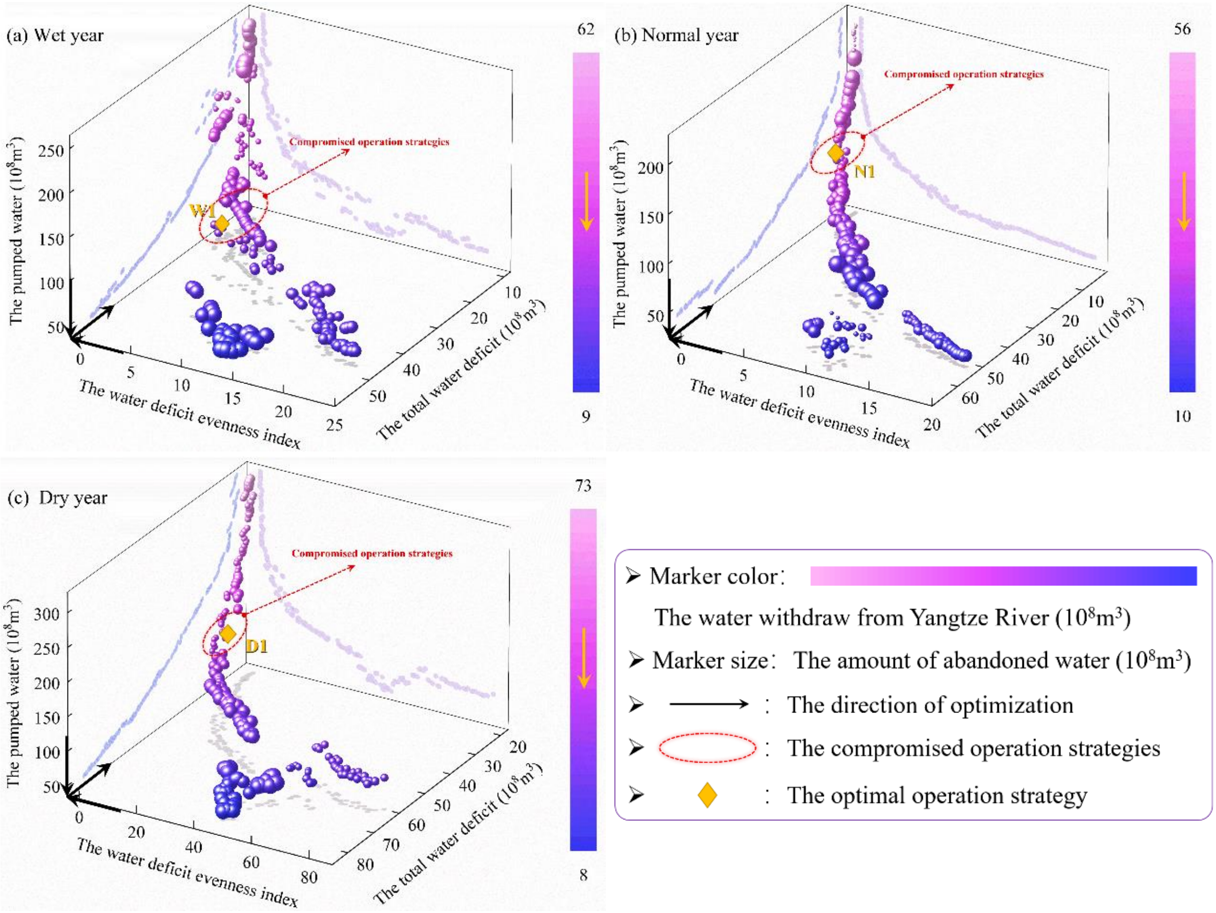

Figure 5: Illustration of Pareto front strategies for (a) wet, (b) normal, and (c) dry years. (W1, N1 and D1 represent the location of the optimal operation strategy in different typical years.)

Fig. 5 provides visualizations of the optimal operation strategy based on Pareto sets in different years. Obviously, the compromised operation strategies are well distributed in three typical years, and the compromised operation strategies and the optimal operation strategy are located in the middle of the curve. The relative relationship between the optimization objectives has been analyzed, the total water deficit has a positive correlation with the water deficit evenness index. In contrast, the total water deficit and water deficit evenness index have a negative correlation with the pumped water, indicating that the water deficit gradually decreases with the increase of PW. The distribution pattern of the marker is formed under the interaction of three objectives (see Fig. 5).

Fig. 5 (a) shows the competitive relationships between TWD, WDEI and PW in wet years that PW decreases sharply and WDEI increases slowly at the beginning when TWD increases by $20\times10^8m^3$, WDEI increases by about $3\times10^8m^3$, and PW decreases by about $164\times10^8m^3$, but when TWD exceeds $31.33\times10^8m^3$, WDEI increases sharply and PW decreases slowly with TWD increasing by $20\times10^8m^3$, WDEI increasing by about $9\times10^8m^3$, and PW decreasing by about $51\times10^8m^3$. The above relationships obey the law of diminishing marginal utility. As a part of PW, the water withdrawn from the Yangtze River represented by the marker color needs to be appropriately pumped according to the natural flow and water demand of users. Generally, the proportion of water withdrawn from the Yangtze in PW cannot be too high, affecting the lake storage capacity and pumping (operating) cost. Therefore, the middle part or the lighter marker color tend to represent better results in the figure. Meanwhile, to reduce the waste of water resources, the amount of abandoned water represented by the marker size should be reduced as much as possible. Therefore, the yellow marker point is obtained as the optimal operation strategy to compare with the historical operation strategy by multi-attribute decision-making. The weights of decision indicators and the results of the comparison are shown in Table 3 and Table 4. Similarly, the Pareto front strategies in Fig. 5 (b) and (c) also follow the above rules, but due to the difference in natural inflow, the specific data are also quite different (see Table 4).

Table 3: Determining the weights of indicators for selecting optimal operation strategy in typical wet, normal, and dry years.

Evaluation indicators	Wet year	Normal year	Dry year
The total water deficit	0.353	0.366	0.402
The abandoned water	0.194	0.203	0.264
The water deficit evenness index	0.207	0.248	0.215
The pumped water	0.134	0.101	0.074
The water withdrawn from Yangtze	0.111	0.080	0.045

3.2 Comparison with historical operation strategy

In order to verify the rationality of the strategies obtained by the joint optimal operation model, this section compares the optimal operation strategy selected in different typical years with the historical operation strategy.

3.2.1 Comparison of the main operation performance indicators

Table 4: Comparison of the main operation performance indicators of the historical and optimal operation strategy in typical years. (units: 108 m^3)

Typical year	Scenario	The total water deficit	The water deficit evenness index	The pumped water	The amount of abandoned water	The water withdrawn from Yangtze
Wet	Historical	65.77	22.87	119.27	374.56	25.74
	Optimal	31.33	4.16	93.62	310.91	23.65
	Decrement	**52.36%**	**81.82%**	**21.51%**	**16.99%**	**8.12%**
Normal	Historical	75.19	26.18	184.06	56.53	42.07
	Optimal	13.49	1.51	100.99	25.17	30.08
	Decrement	**82.06%**	**94.24%**	**45.13%**	**55.47%**	**28.50%**
Dry	Historical	63.22	21.54	159.88	13.60	26.62
	Optimal	39.39	5.01	154.68	0.05	37.34
	Decrement	**37.69%**	**76.72%**	**3.25%**	**99.63%**	**-40.27%**

Table 4 shows the optimal historical operation strategy in typical years. Compared with the optimal operation strategy, the TWD and WDEI of the historical operation strategy are very high, which means that the water deficit concentration in the historical operation strategy leads to the inability to reduce the TWD. Meanwhile, the PW and abandoned water are slightly large, indicating that the historical operation strategy has more disadvantages on economic and ecological benefits. WDEI can directly reflect the difference of water deficit among users. WDEI has sound optimization effects, of which the reduction in the optimal operation strategy was 94.2% (81.8 %, 76.7%) of the historical values in the typical normal year (wet year and dry year). The optimized operation strategy can significantly reduce TWD and PW by 82.06% (37.69%, 52.36%) and 45.13% (3.25%, 21.51%) compared with the historical values, respectively, while maintaining a very low WDEI. It has been demonstrated to be an excellent strategy for inter-basin water diversion, which can make multiple users share the risk of water deficit and alleviate the problem of water deficit concentration. The reduction of the abandoned water and the water withdrawn from the Yangtze River represents an increase in the lake storage capacity. The amount of abandoned water of the operation strategy is greatly reduced, and the amount of abandoned water is only 0.051×10^8m^3 in the dry year. This indicates that the optimal operation can maximize the utilization efficiency of the limited water resources. However, the of amount of water withdrawn from the Yangtze River increased by 10.72×10^8m^3 after optimization in dry years, indicating that the proportion of the water withdrawn from Yangtze River in PW was raised in the optimal operation strategy to ensure uniform distribution of water and higher economic benefits.

3.2.2 Comparison of water deficit in water users

The comparison of water deficit in water users between the optimal operation strategy and the historical operation strategy in three typical years is illustrated in Table 5, which more intuitively reflects the optimization effect of WDEI. The 'Variance' and 'Decrement' represent the difference between the maximum and minimum values and the percentage reduction, respectively. The study found that after optimization, the variance of the users was reduced by 62.93 % (78.07 %, 54.09 %) in different typical years (i.e., bold font in Table 5). FHH user, S-Z user and HZH user, which have large water deficit in the historical operation strategy, decrease by 14.63 (14.41, 14.69) $\times10^8$m^3, 5.61 (9.33, 1.77) $\times10^8$m^3 and 0.98 (7.98, 5.26) $\times10^8$m^3 of the optimal operation strategy, respectively (see Table 5). The possible reason for the large water deficit of users is that they are far away from the main lakes and rivers, or there are many users on the water transmission route that need to be supplied. Users jointly share the water deficit risk in the optimal operation strategy in the case of little natural flow. The difference between the maximum and minimum water deficit is controlled within 8×10^8m^3, where the difference in the normal year is only 3.13×10^8m^3, and the problem of water deficit concentrated in a particular user is alleviated. For example, in the dry year, the water deficit of users under optimal operation strategy ranges from 0 to 7.64×10^8m^3. Although the water deficit of GLH-HA user, LMH user, and WSH user is slightly higher after optimization, the total water deficit is much lower than the historical value and isn't concentrated in FHH user, HZH user, and S-Z user, compared with the results of historical operation. Overall, the optimal operation strategy is more reasonable, and may accord with the aspirations of both the government and the general public.

Table 5: Comparison of water deficit in water users for (a) wet, (b) normal, and (c) dry years.

Typical years	Wet year		Normal year		Dry year	
Users	Historical	Optimal	Historical	Optimal	Historical	Optimal
LYH user	5.04	0.00	10.94	0.00	2.78	2.68
JBHD user	0.52	0.00	0.00	0.00	0.00	0.00
SH user	1.97	0.92	0.00	0.00	0.52	0.52
GLJ-HA user	3.98	1.78	11.28	1.91	2.69	3.40
HZH user	7.07	6.19	8.35	0.38	8.66	6.70
FHH user	17.22	2.59	14.41	0.00	16.64	1.95
LYG user	7.44	2.15	1.68	0.00	6.10	3.82
EH-HY user	3.11	3.09	1.73	0.50	6.06	4.55
S-Z user	11.28	5.67	12.46	3.13	9.41	7.64
S-S user	1.02	0.32	1.39	0.49	1.34	0.74
S-P user	3.62	1.35	4.15	1.55	5.11	3.08
LMH user	0.58	0.12	2.69	2.37	1.35	2.53
WSH user	2.91	3.21	6.10	3.16	2.55	3.64
Variance	22.87	4.16	26.18	1.51	21.54	5.01
Decrement	81.82%		94.24%		76.72%	

3.2.3 Comparison of the operation water level of the Hongze and Luoma lake

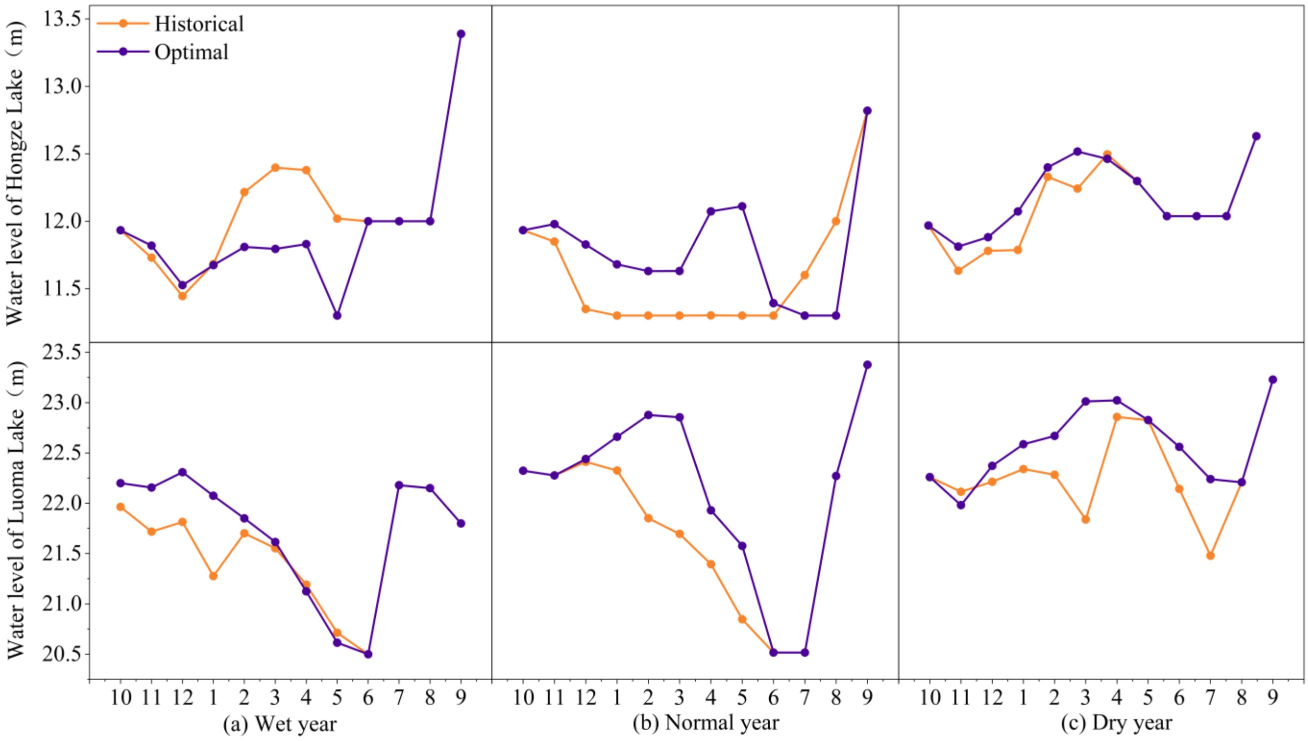

Figure 6: The operation water level of the Hongze and Luoma lake for (a) wet, (b) normal, and (c) dry years under historical (orange line) and optimal (purple line) operation.

Fig. 6 shows the water level variations of HZ Lake and LM Lake (two major storage lakes in Jiangsu Province). The water level of HZ Lake and LM Lake is slightly higher than the historical value after optimization for most of the time. Both lakes show a regular trend of change: the lake remains at a high level during the dry season, releases water before the flood season, then remains at a low level throughout the flood season for storing flood, and returns to a high level at the end of the flood season. Therefore, the water transmission system can simultaneously implement lake water storage in the flood and non-flood seasons to ensure the fulfilment of water supply tasks and improve the utilization efficiency of water resources.

The optimized water level of HZ Lake was significantly lower than the historical value from February to June in Fig. 6 (a). This is due to the large amount of natural precipitation with uneven spatial-temporal distribution in the wet year, and the discharge time and discharge volume of HZ Lake are unreasonable in historical operating strategy, resulting in a large amount of water deficit and abandonment. Therefore, in the optimized operation strategy, a certain amount of lake water is discharged during the impoundment period for water supply. Similarly, LM Lake level in April-June below the historical level. In the Fig. 6 (b) and (c), the optimized HZ Lake level is significantly higher than the historical value before the flood season, while the flood season is decreased dramatically, indicating that the lake stores a certain amount of water while supplying water during the impoundment period, and discharges water before the flood season to ensure that the flood season is at a safe level. Similarly, for LM Lake, the water level increased after optimization in typical years, and tended to be consistent after the flood season.

Compared with the historical operation strategy, the water level of HZ Lake and LM Lake is slightly higher than the historical value after optimization for most of the time. Combined with the results of Table 4 and Table 5, the coordinated water diversion between LM Lake and HZ Lake increased obviously while reducing TWD and PW.

3.2.4 Comparison of the water distribution of different routes between two adjacent lakes

Table 6: The water distribution of different routes between two adjacent lakes.

Inflow/ outflow Lake	Inflow/ outflow Route	Multi-year average	
		Historical	Optimal
Outflow LM Lake	The ratio of inflow Hanzhuangyun and Bulao River	19: 8	1: 1
Inflow LM lake	The ratio of outflow Zhongyun and XuhongRiver	7: 9	7: 1
Outflow HZ Lake	The ratio of inflow Xuhong and Zhongyun River	1: 6	1: 14
Inflow HZ Lake	The ratio of outflow Liyun River and Jinbao channel	19: 1	25: 1
Water withdrawn from Yangtze River	The ratio of inflow Jinbao channel and Liyun River	8: 9	2: 9

This paper considers that the water distribution of different routes between two adjacent lakes is an important factor affecting the water deficit in the users. The water transmission capacity of the route is mainly affected by the water demand of users and the pumping capacity of the pumping station along the way. Table 6 shows the distribution of different water transmission routes between neighboring lakes in typical years. The ratio of water pumped from LM Lake into Hanzhuangyun River and Bulao River is decreased from 19: 8 to 1: 1, which is convenient for simultaneous double-route water supply outside the province and reduces the water supply pressure of Hanzhuangyun River. The ratio of water from the Zhongyun River and the Xuhong River to the LM Lake increased from 7: 9 to about 7: 1, gradually shifting the focus of the water transmission route to the Zhongyun River. The reason is that Hongze Lake transports water to the Zhongyun River through the Erhe and Gaoliangjian Sluice without pumping, which can reduce the pumped water and save project cost. In addition, there are many users in Zhongyun River, the water demand is higher. When the water supply is sufficient, the drainage through Huaiyin, Yanhe and Yangzhuang Sluice significantly reducing the water deficit of FHH and LYG users (see Table 5). Similarly, the ratio of water from HZ Lake to Zhongyun River and Xuhong River increased from 6:1 to 14:1. The ratio of pumping water from Liyun River and Jinbao Waterway to HZ Lake also increased from 19:1 to 25:1, indicating that the water transport efficiency of Zhongyun River is higher, and the operation strategy should be based on water transfer from the central canal, with the western route as the auxiliary support route. Similarly, the ratio of pumping water from the Yangtze River to the Liyun River and the Jinbao Channel has also increased (see Table 6).

4 Discussion

Inter-basin water transfer projects are widely used around the world and are also quite costly to construct. For instance, the Colorado River aqueduct cost approximately 3.5 billion dollars (Witcher, 2017), the Australian Snowy Mountains Scheme was completed in 1974 at a cost of about 500 million dollars (Pigram, 2000), and the South-to-North Water Diversion Project in China, as the largest and most expensive inter-basin water transfer system in the world, is projected to cost 62 billion dollars (Markosov, 2014). The installation and operation maintenance costs are also significantly high. Of this, the investment for just the Eastern Route of the project is around 1 billion dollars (Liu et al., 2022), which is a typical example of a vast and complex water transfer system and has certain representativeness. Therefore, the Jiangsu section of the Eastern Route of the South-to-North Water Diversion Project is selected as the study area for this paper.

The joint optimal operating model is operated based on ecological (the total water deficit), social demand (the evenness of water deficit) and economic (the pumping water) objectives, focusing on the issue of water deficit concentration. Herein, the limited available water is used to minimize the total water deficit of the system and water deficit differences between users and applies to inter-basin water transfer projects with complex systems and a large number of water users. The multi-attribute decision implemented in this study incorporates ecological (the abandoned water) and the water withdrawn from Yangtze River into the multi-attribute decision indicator set, which can provide optimal operation strategy with preferred weights for decision makers who have different preferences.

Evidence from this research suggests that the water extracted from Hongze Lake is much greater than that from other lakes, indicating that Hongze Lake is the main source of water to support water supply and flood control within the system. Therefore, it is important to understand the water storage period. It is important to ensure that the water level of each storage lake reaches the water level at the end of the flood season to complete the water allocation in the non-flood season. If the reservoir water storage is insufficient, the Yangtze River will be pumped in time to ensure the normal operation of the entire water diversion project. The Yangtze River is the main source of water outside the J-SNWDP system. The proportion of pumping water from the Yangtze River in the pumping water volume of the system plays an important regulatory role. The actual operation should follow the following priority rules: When the natural inflow is less, mainly through pumping the Yangtze River to complete the task of water supply; when the natural inflow is large, the water withdrawn from Yangtze River is reduced, and the focus of water allocation is shifted to the mutual replenishment between lakes.

In summary, it can be seen that the water deficit doesn't only occur under less natural inflow conditions, but also there are still serious problems of water deficit and abandonment in wet years. The main reasons for the coexistence of water deficit and water abandonment are lakes' limited water storage capacity and the uneven spatial-temporal distribution of natural inflow. Water deficit and the pumped water are greatly affected by natural inflow; we should not expect to find a general operating strategy optimal in all natural conditions. This paper performs well in water resources allocation and utilization on a monthly time step of three typical years (wet year, normal year and water deficit year), which is representative and universal, and provides a useful guide for IBWT under future uncertainty. Therefore, in addition to implementing the optimal operation strategy, the flood control limit water level should be appropriately increased according to the natural inflow to improve the lake's storage capacity in the flood season. This is a potential way to effectively enhance the operational efficiency of inter-basin water transfer project.

5 Sources of Uncertainty

This paper proposes an optimal operation strategy that considers the evenness of water deficit, accounting for the hydrological conditions of three typical years (i.e., wet years, normal years, and dry years). The strategy can generally alleviate the concentration of water deficit under most natural inflow conditions. However, due to the impact of global climate change, future runoff is highly uncertain, necessitating further discussion. Moreover, the Eastern Route of the South-to-North Water Diversion Project is a large-scale inter-basin water transfer project that spans provinces such as Jiangsu and Shandong, and it involves numerous uncertain factors. These include changes in biological communities, hydrological variations, and dynamic changes in water demand caused by extreme events, all of which add complexity to determining the water supply capacity of the project.

Regarding the two major regulating reservoirs within Jiangsu, Hongze and Luoma Lakes, the operational control water levels used in this paper were approved and established by the Ministry of Water Resources of China in 1954. Over the years, with socio-economic development, changes in the South-to-North Water Diversion Project, and the flood control capabilities of the lakes themselves, the original flood limit water levels have become inadequate for current development needs. This paper proposes the idea of appropriately raising the flood limit water levels of the lakes during the flood season, but the specific values require further research, incorporating runoff forecasting, flood risk early warning, and other factors into future studies of inter-basin water transfer.

Furthermore, this paper places greater emphasis on the positive impacts of inter-basin water transfer on social demands and ecology, with less focus on the analysis of economic costs. Due to the variability in water prices across different regions and the ongoing changes in economic development in recent years, the cost of the project is currently represented by the volume of water pumped and has not been converted into actual cost prices. Future studies will delve into the dynamic adjustment mechanisms of water pricing, subsequently analyzing the economic benefits of the project.

5 Conclusions

Scientific operational decisions in inter-basin water transfer projects are important for improving the water allocation balance and reducing the stress of concentrated water deficits. As the largest and most heavily invested inter-basin water transfer project in the world, the South-to-North Water Transfer Project, has been selected as the research area for this paper, focusing specifically on the Jiangsu section.

(1) From the perspectives of social demand, economy and ecology, this paper establishes a joint optimal operation model for the Jiangsu section of the South-to-North Water Diversion Project (J-SNWDP), and further uses a combination of NSGA-III algorithm and multi-attribute decision-making for strategy preference, which has a certain persuasion. This method has a good performance in solving the complex water transfer problems with multiple objectives and engineering units, and is currently less applied.

(2) After incorporating the Water Deficit Evenness Index into the model, the concentration of water deficit is reduced by 94.2% (81.8 %, 76.7%) in typical wet years (normal year and dry year) compared with the historical strategy, which greatly ameliorated the engineering problem of user water deficit concentration. The other two indicators of the model, total water deficit (TWD) and pumping water (PW), were reduced by 82.1% (37.7%, 52.4%) and 45.1% (3.2%, 21.5%), respectively, with excellent performance.

(3) After optimization, the rising trend of water level in Hongze Lake and Luoma Lake reflects the enhanced storage capacity of the lake, and the water allocation between different water transmission routes is more balanced, which improves water utilization and water supply efficiency. Moreover, this paper proposes water transfer prioritization rules and suggests appropriately increasing the flood control limit water level, aimed at protecting the water diversion and enhancing operational efficiency. The sources of uncertainty, such as natural inflow and societal water demand, are worthy of further study.

Overall, the successful application of the optimal operation strategy in the Jiangsu section of the South-to-North Water Transfer Project also demonstrates the feasibility of the research. It is hoped that this method can be attempted in other similar watersheds worldwide in order to revalidate this method in other circumstances, demonstrate its universality. This would provide the scientific basis and operating suggestions for the inter-basin water diversion project.

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Data availability

Data will be made available on request.

Author contribution

Bingyi Zhou: Writing- Original Draft, Validation, Formal analysis, Software, Methodology, Conceptualization, Visualization, Term Definition

Guohua Fang: Writing- Review and Editing, Funding acquisition, Resources, Supervision, Project administration

Xin Li: Resources, Writing- Review and Editing, Visualization, Investigation.

Jian Zhou: Writing- Review and Editing, Supervision, Formal analysis.

Huayu Zhong: Resources, Data Curation, Visualization, Investigation.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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