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Multi-scenario optimization model for operation of inter-basin water transfer-supply systems considering cost–benefit relationships

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ABSTRACT

The optimized operation of an inter-basin water transfer system is a widely used approach to achieving optimized regional water resource allocation. The costs of water transfers vary considerably, depending on the composition of the water source, the target audience and the route and distance of the transfer. This study proposes a multi-scenario optimization model for the operation of inter-basin water transfer-supply systems that balances the cost–benefit relationships. A two-objective optimization model is first established including minimizing the sum of squared water supply deficits and the cost of water transfers. Three water transfer scenarios are developed for different cost–benefit relationships. Based on these scenarios, the established optimization model is further converted into a single-objective optimization model to avoid the direct calculation of complex water transfer costs. The model is finally solved to obtain water transfer schemes. The proposed model is applied to the eastern route of the South-to-North Water Diversion Project in China. The results show that with a contracted diversion of 60% of the Yangtze River, the reliability of the water supply is 78.2% and the water shortage index is 2.8%, which is a compromise between balancing the water shortage index and the volume and cost of water transfer.

Key words: east route of the South-to-North Water Diversion Project, inter-basin water transfer, multiple water sources, multi-scenario model, optimized operation model

HIGHLIGHTS

- A multi-scenario optimization model for the operation of inter-basin water transfer-supply systems considering cost–benefit relationships is proposed.
- The established optimization model is converted based on developed scenarios to avoid the direct calculation of complex water transfer costs.
- The proposed model is applied to the eastern route of the South-to-North Water Diversion Project in China.

1. INTRODUCTION

The shortage of water resources has become a serious obstacle to sustainable economic and social development over the past few decades (Wang *et al.* 2021; Chen *et al.* 2023). Water use in many areas is close to exceeding the maximum acceptable water use in the basin, which leaves some administrative areas with serious water management problems (Peng *et al.* 2017; Wang *et al.* 2023). Inter-basin water transfer is an effective way to address the uneven distribution of regional water resources. The optimized operation of an inter-basin water transfer system is a widely used approach to achieving optimized regional water resource allocation (Wang *et al.* 2015; Cirilo *et al.* 2021; Ye *et al.* 2023). Improving the efficiency of water use and reducing the cost of water transfer through the joint optimization of multiple water sources is essential (Rosenberg *et al.* 2008; Xu *et al.* 2016, 2023). One of the key issues is how to coordinate the allocation of local and diverted water resources in space and time so that the issues of 'when to supply' and 'when to divert' are addressed at an operational level.

Multiple water source allocation in regional water resource systems has become a hot topic of research over the past few years, especially since the commissioning of water conservation projects such as the South-to-North Water Diversion Project

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in China. Many scholars have developed mathematical models for this purpose. Initially, optimization strategies were usually proposed to minimize the occurrence of water shortages or to maximize the reliability of water supply (Zeng *et al.* 2014; Spiliotis *et al.* 2016; Gu *et al.* 2017), and it was achieved by regulating the operational rules for water delivery and supply. The optimized allocation of multiple water resources has become increasingly effective over time, particularly in terms of the amount of water transferred. With the development of large-scale construction projects, the cost of water transfers has become an issue that cannot be ignored and multi-objective decision analysis based on the marginal benefits of water transfers and water supply reliability is applied to the allocation of multiple water sources (Wang *et al.* 2023). Harou *et al.* (2009) assessed the economic value of water resources based on system analysis and evaluated the linkages between water resource systems and economic activities, leading to an efficient allocation of water resources and the consequent greater social and economic benefits. Chen *et al.* (2013) investigated the applicability of a two-tier pricing scheme to balance water allocation by using the Stackelberg game model and applied it to the operational management level. The operating model based on maximizing economic efficiency is related to the cost of diverting water. The parameters of the model are difficult to calibrate, as not only construction and operating costs need to be considered, but also the cost of compensation for ecological damage (Matete & Hassan 2005, 2007). Zhang *et al.* (2017) established a theoretical framework for inter-basin water transfer systems and proposed a corresponding water transfer scheme that takes into account the costs and benefits of water use to some extent. However, the costs of water transfers vary considerably, depending on the composition of the water source, the target audience and the route and distance of the transfer. With the cost of water transfer directly incorporated into the calculation, multi-objective optimization problems for water transfer-supply systems will become more high-dimensional and complex (Zhang *et al.* 2021; Wang *et al.* 2022). This study proposes a multi-scenario optimization model for the operation of inter-basin water transfer-supply systems, aiming to provide a feasible approach for developing optimized operation schemes by fully considering the cost–benefit relationships of water transfer. A two-objective optimization model is first established including minimizing the sum of squared water supply deficits and the cost of water transfers. Three water transfer scenarios are developed for different cost–benefit relationships. Based on these scenarios, the established optimization model is further converted into a single-objective optimization model to avoid the direct calculation of complex water transfer costs. The model is finally solved to obtain water transfer schemes and the schemes are evaluated using water supply reliability and a water shortage index. The proposed model is applied to the eastern route of the South-to-North Water Diversion Project in China (ER-SNWDP), demonstrating how the model promotes the efficient usage of multiple water resources in space and time, demonstrating how the model can facilitate the efficient use of multiple water resources in space and time while taking into account the cost–benefit relationships.

2. STUDY AREA AND DATA

The case study was conducted in the ER-SNWDP, located in the center of Jiangsu Province, China. The study area covers 43,143 km^2, 83% of which is cultivated. The water resources system consists of several water sources including the Hongze Lake, the Luoma Lake and the ER-SNWDP, as well as inflow channels formed by river networks, and links to the Yangtze River, Huaihe River and the Yishusi basin (Liu & Zheng 2002; Du *et al.* 2016).

The Hongze Lake and the Luoma Lake account for most of the water supply and as such they are considered to be important regulating reservoirs. The natural inflow to the Hongze Lake comes from the Huaihe River basin, the natural inflow to the Luoma Lake comes from the Yishusi basin, while the local inflow between the two lakes is supplemented by precipitation. The hydrology and meteorology around the two lakes are often inconsistent. When alternating wet and dry conditions occur throughout the region, water from the Hongze Lake and the Luoma Lake can be exchanged with each other via the Grand Canal and its parallel channels. Water is pumped from the Hongze Lake to the Luoma Lake at the Sihong, Suining and Pizhou stations (the parallel channels) and at the Siyang, Liulangjian and Zaohe stations (the Grand Canal). Conversely, in order to transfer water from the Luoma Lake to the Hongze Lake, sluice gates are opened in order to transfer it by gravity. In case of drought, when the water resources of the two local lakes cannot meet the water demand, water is pumped from the Yangtze River and transferred to the Hungze Lake and the Loma Lake. The water resources system is designed according to the compensatory relationship between the different water sources and the supply and demand relationships are shown in Figure 1, as well as the water sources and users.

As shown in Figure 1, the study area covers the cities of Huaian, Suqian, Xuzhou, Lianyungang and parts of Yangzhou city (Jiangdu, Gaoyou and Baoying county) and Yancheng city (Funing county). Due to the large number of users and for clarity's

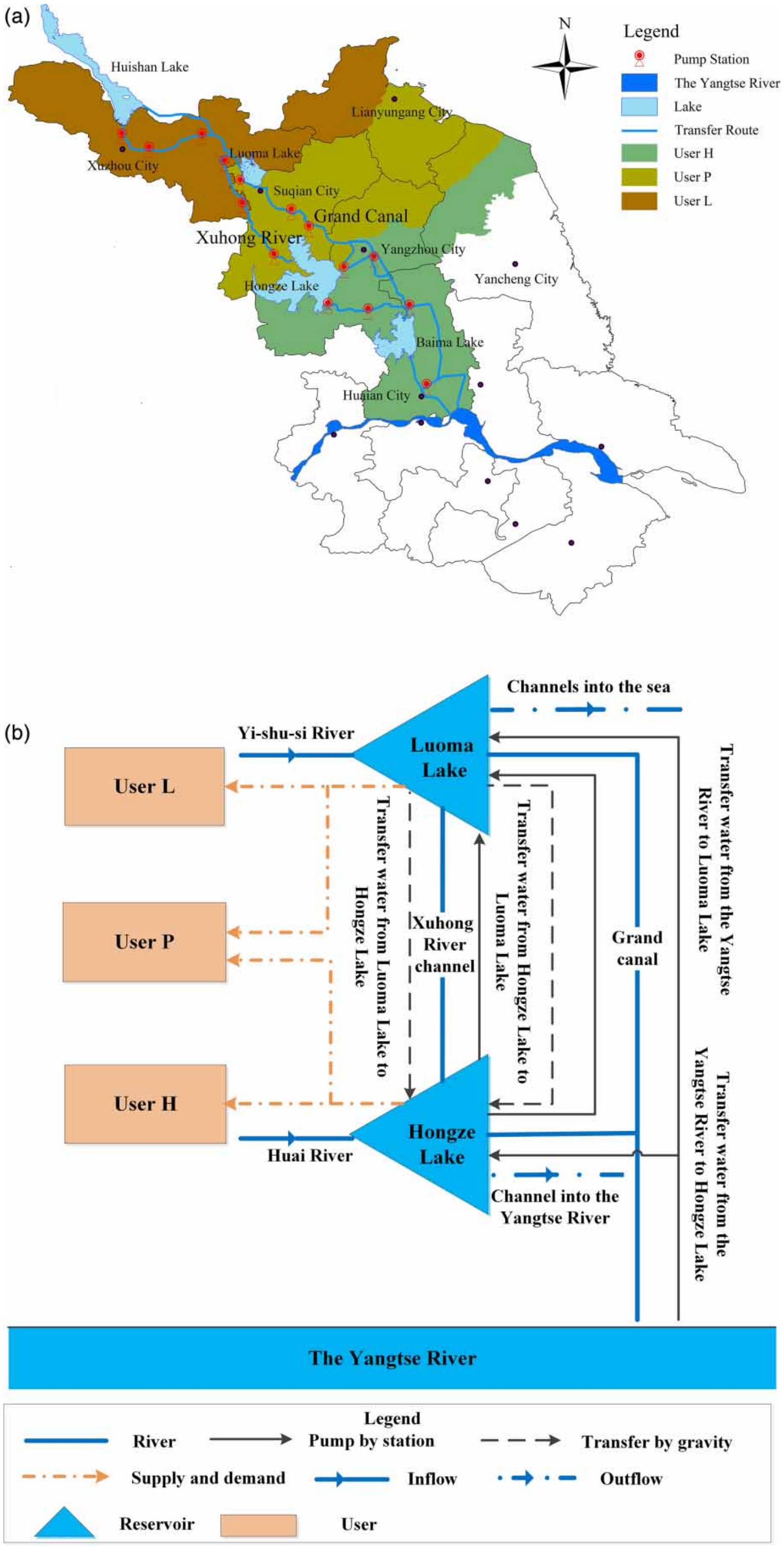

Figure 1 | Map of the study area and the eastern route of South-to-North Water Diversion Project: (a) map and (b) generalized diagram. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wcc.2023.259.

sake, this paper divides the intake area into three parts and summarizes the water usage for each part. Considering the constraints on the inflow passage of the water supply and the costs of water transfer, the relationship between supply and demand is defined as follows:

(1) The user L (brown area in Figure 1) is supplied with water by the Luoma Lake.
(2) The user P (yellow area in Figure 1) is supplied with water by both the Hongze Lake and the Luoma Lake.
(3) The user H (cyan area in Figure 1) is supplied with water by the Hongze Lake.

According to Table 1, the monthly target water supply requirement is concentrated between June and August due to the greater agricultural water demand at this stage. According to Table 2, the upper bound of reservoirs is smaller from July to September due to flood control requirements. Figure 2 shows the runoff time series to the Hongze Lake and the Luoma Lake (Burgan *et al.* 2017; Chebana & Ouarda 2021).

3. METHODS

3.1. Optimization operation model

In order to determine the optimized operation policy of the inter-basin water transfer-supply system, the following issues have to be addressed:

(1) The cost of using inter-basin water transfers is higher than the cost of local water supplies due to the high construction and operating costs of inter-basin transfer projects. It is therefore important to consider the economics of inter-basin water transfer-supply systems.
(2) The outcome of the water supply from the two sources depends on the synchronicity or non-synchronicity of the inflows between the source and the receiving area, which is determined by the variation in the spatial and temporal distribution of the water supply from the two things.
(3) The annual diversion of water from the Yangtze River is affected by a number of factors, such as the water supply quotas of other provinces and cities such as Shandong and Tianjin, as well as the storage capacity of the water conservancy project infrastructure in the surrounding areas.

To address these issues, we propose a multi-scenario optimized operational model. The impact of economic costs is addressed by setting up operational scenarios for the hydrological project, while synchronicity or non-synchronicity of inflows is dealt with by setting up two lakes with different combinations of inflow patterns.

3.1.1. Objective function

The model is based on two objective functions (Hsu & Cheng 2002; Ahmadianfar *et al.* 2017) for the shortage of water resources and the cost of water transfer, respectively. The first function minimizes the sum of the squares of the water

Table 1 | The monthly target water supply requirement of different users

Users	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
User H ($\times 10^8$ m^3)	1.2	1.3	3.0	3.1	3.6	14.4	10.9	10.3	4.9	1.4	1.3	1.7
User L ($\times 10^8$ m^3)	0.2	0.2	0.6	0.6	0.8	3.3	2.5	2.3	1.0	0.2	0.2	0.3
User P ($\times 10^8$ m^3)	1.5	1.6	4.3	4.5	5.4	22.8	17.1	16.3	7.4	1.8	1.7	2.2

Table 2 | The monthly storage bounds of different lakes

Lake		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hongze ($\times 10^8$ m^3)	Upper	30.1	30.1	30.1	30.1	30.1	22.3	22.3	22.3	22.3	30.1	30.1	30.1
	Lower	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Luoma ($\times 10^8$ m^3)	Upper	8.3	8.3	8.3	8.3	8.3	7.1	7.1	7.1	7.1	8.3	8.3	8.3
	Lower	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5

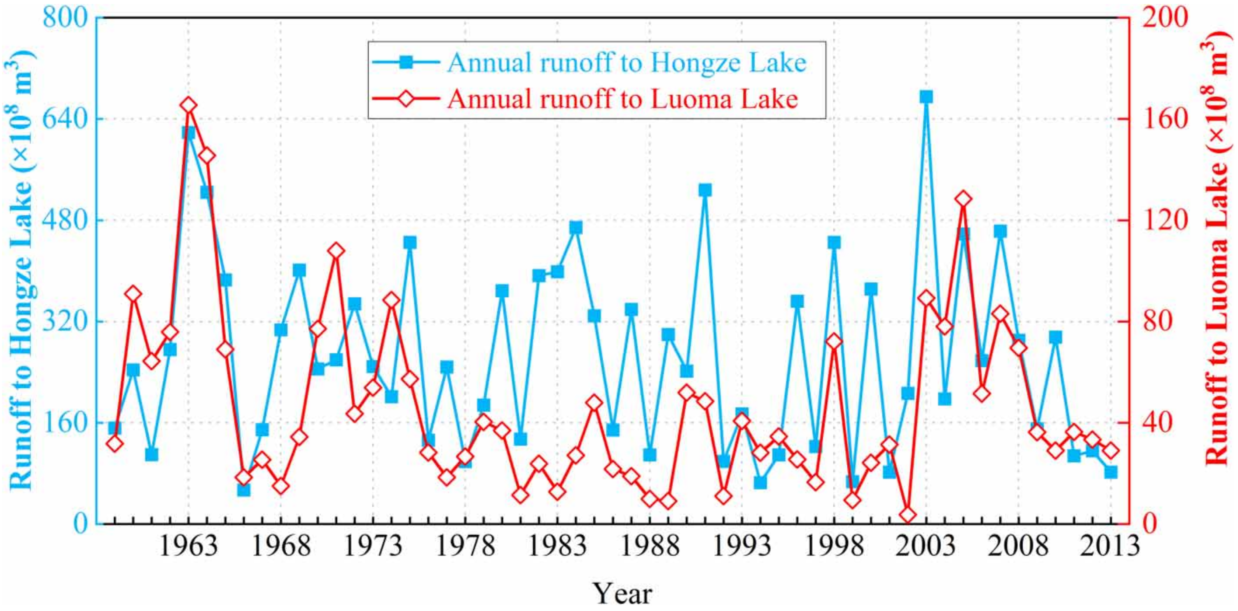

Figure 2 | Runoff time series to the Hongze Lake and the Luoma Lake.

supply deficit occurring during the system operation:

$$\min \mathrm{SI} = \frac{1}{M \cdot T} \cdot \sum_{i=1}^{M} \sum_{t+1}^{T} \left(\left(D_t^i - \sum_{j=1}^{N} R_t^{j,i} \right) / D_t^i \right)^2 \tag{1}$$

The second function minimizes the cost of water transfer:

$$\min \mathrm{Cost} = \sum_{t=1}^{T} (k_1 \cdot W_t^1 + k_2 \cdot W_t^2 + k_3 \cdot W_t^3) \tag{2}$$

where M is the total number of users (1 for user H, 2 for user L and 3 for user P); N is the total number of reservoirs (1 for the Hongze Lake, 2 for the Luoma Lake and 3 for the Yangtze river); T is the total number of time steps; $R_t^{j,i}$ corresponds to the water delivered from the water source j to the user i; D_t^j is the target water supply requirement for user i; W_t^1 is the quantity of water diverted through a sluice; W_t^2 is the quantity of water diverted through pump stations and W_t^3 is the quantity of water diverted through the Yangtze river. k_1 is the unit cost of W_t^1; k_2 that of W_t^1 and k_3 that of W_t^3. The unit for all volumes of water is a million m^3.

In order to better reflect the degree of water shortage in the system, we define the integrated water shortage index so that it has the same unit as the water shortage index (SI) in the traditional sense, and is written as SI$^{1/2}$.

3.1.2. Constraints

The model established for this study should satisfy physical limitations, such as the mass balance equation, the water transfer capacity and the permissible bounds of water storage, as well as other constraint conditions. These constraints are described as follows.

The mass balance equation applied for the water quantity in the Hongze Lake is:

$$S_{t+1}^1 = S_t^1 + I_t^1 + Tra_t^1 - Tra_t^2 + Div_t^1 - (R_t^{1,1} + S_t^{1,3}) - SP_t^1 \tag{3}$$

And for the Luoma Lake:

$$S_{t+1}^2 = S_t^2 + I_t^2 + Tra_t^2 - Tra_t^1 + Div_t^2 - (R_t^{2,2} + S_t^{1,3}) - SP_t^1 \tag{4}$$

The permissible bounds of water storage are defined by:

$$S_t^{j,\min} \le S_t^j \le S_t^{j,\max}, j = 1, 2 \tag{5}$$

The water transfer capacity is as follows:

$$0 \le Div_t^j \le Div_t^{j,\max}, j = 1, 2 \tag{6}$$

$$0 \le Tra_t^j \le Tra_t^{j,\max}, j = 1, 2 \tag{7}$$

Another constraint is the impossibility for the Hongze Lake and the Luoma Lake to transfer water to each other at the same time:

$$Tra_t^1 \cdot Tra_t^2 = 0 \tag{8}$$

Lastly, all variables are non-negative. In Equations (3)–(8), S_t^j and S_{t+1}^j are the initial and ending water storage at time period t; $S_t^{j,\min}$ and $S_t^{j,\max}$ represent the lower and upper bounds of water storage; I_t^j is the natural inflow to the reservoir; Tra_t^1 is the controlled inflow from the Luoma Lake to the Hongze Lake; Tra_t^2 is the controlled inflow from the Hongze Lake to the Luoma Lake; Div_t^j is the controlled inflow from the Yangtze river to the reservoir; SP_t^j is the amount of spill when the storage in the reservoir exceeds the maximum storage; $Div_t^{j,\max}$ is the water diversion capacity for the donor reservoir and $Tra_t^{j,\max}$ is the water diversion capacity for the Yangtze River.

3.2. Model parameters determination under different model scenarios

As inter-basin water management-related diversions increase, the ecological and energy consumption impacts increase non-linearly (Cabo *et al.* 2014), making it complex to build an integrated scheme to determine these costs. Here, the two-objective optimization for the allocation of water resources is converted to a single objective by taking annual diverted water from the Yangtze River as the constraint on the maximum volume of diverted water. The different operation scenarios are then run in the optimization model and solved separately in order to avoid direct calculation of economic costs. A flowchart of the proposed approach is shown in Figure 3.

There are three sources of water supply: local water resources generated by the rainfall-runoff from the catchment area of the two lakes; water transfer from the Hongze Lake to the Luoma Lake and diverted water from the Yangtze River. Local water resources can be distributed via the gravity flow formed by the rainfall-runoff and requires the lowest energy consumption, and hence the lowest economic cost. In the second type, water is pumped and transferred from the Hongze Lake to the Luoma Lake from multiple pumping stations, which requires higher energy consumption and economic cost. Lastly, the long-distance water diversion from the Yangtze River to the Hongze Lake and the Luoma Lake demands the highest energy consumption and economic cost. The supply from these different water sources should be allocated with different priorities according to their cost, which is allowed by the multi-scenario analysis described below.

Scenario 1 involves low water transfer costs, only considering local water resources. The corresponding parameters are set by: $W_t^1 \ge 0$, $W_t^2 = 0$, $W_t^3 = 0$. Its operational scenario is shown below:

$$Tra_t^1 \ge 0,\ Tra_t^2 = 0,\ \sum_{j=1}^{N} Div_t^j = 0 \tag{9}$$

In scenario 2, the water transfer costs are around average and include the cost for diverting water from the Hongze Lake to the Luoma Lake: $W_t^1 \ge 0$, $W_t^2 \ge 0$, $W_t^3 = 0$. Its operational scenario parameters are set as follows:

$$Tra_t^1 \ge 0,\ Tra_t^2 \ge 0,\ \sum_{j=1}^{N} Div_t^j = 0 \tag{10}$$

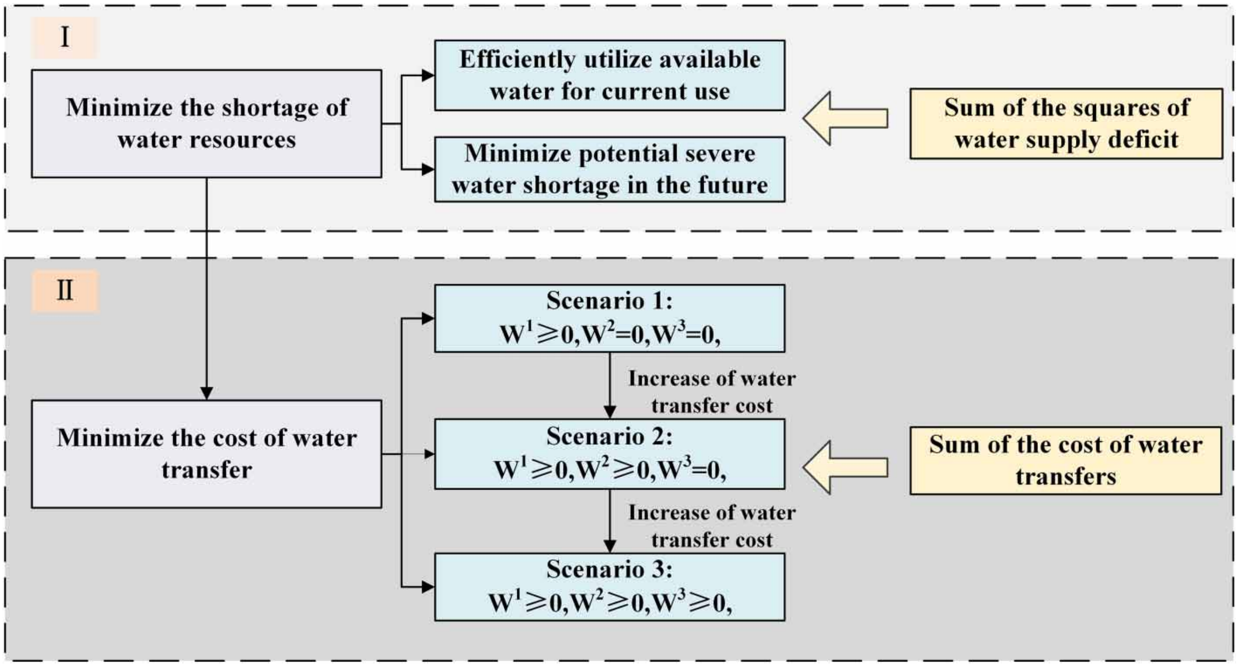

Figure 3 | The flowchart of the model parameters determination under different scenarios.

Lastly, scenario 3 considers high water transfer costs which comprise the cost of diverting water from the Yangtze River $W_t^1 \geq 0$, $W_t^2 \geq 0$, $W_t^3 \geq 0$. Its operational scenario parameters are given by:

$$Tra_t^1 \geq 0,\ Tra_t^2 \geq 0,\ 0 \leq \sum_{j=1}^{N} Div_t^j \leq Dc \tag{11}$$

Dc is the contracted amount of annually diverted water from the Yangtze River, in million m^3.

4. RESULTS

4.1. Water balance results under different scenarios

The input data consists of the hydrological records of the inflow to the Hongze Lake and the Luoma Lake from 1966 to 2020. The results of the water shortage index (calculated with the lingo software) (Sharif & Swamy 2014) are shown in Figure 4.

Under the conditions of scenario 1, water scarcity occurs in the water supply system when the exceedance probability of inflow to Hongze Lake is more than 50% and that of the Luoma Lake is more than 40%. The water shortage index increases gradually from 0.05 to 0.60 with the decrease of inflow from the Hongze Lake and the Luoma Lake (an increase in probability indicates a decrease in inflow). The variation rule of the water shortage index under scenario 2 is similar to that of scenario 1. In this case, the rate can be reduced to a certain extent by transferring water from the Hongze Lake to the Luoma Lake especially while the inflow of the Hongze Lake is high relative to that of the Luoma Lake, i.e., if the exceedance probability of inflow to the Luoma Lake varies between 40 and 60% and that to the Hongze Lake is more than 80%. Transferring water from the Hongze Lake to the Luoma Lake plays an important part in the compensation, and contributes to the reduction of the water shortage of user L and user P. The constraint for annually diverted water under scenario 3 limits the volume of diverted water to 7.6 billion m^3. It is obvious that the diverted water from the Yangtze River can alleviate the water shortage in the water resources system. The problem of water scarcity mostly exists when the probability of water shortage in the Hongze Lake is greater than 90% and that of the Luoma Lake is greater than 40%, however, it is limited to 0.05–0.10 when water is allowed to be diverted from the Yangtze River (scenario 3). These results show that the role of alleviating the water shortage based on the inflow of the two lakes alone is limited. The water will indeed be in great shortage without water diversion from the Yangtze River, which has a greater influence on the inflow of the Hongze Lake than that of the Luoma Lake.

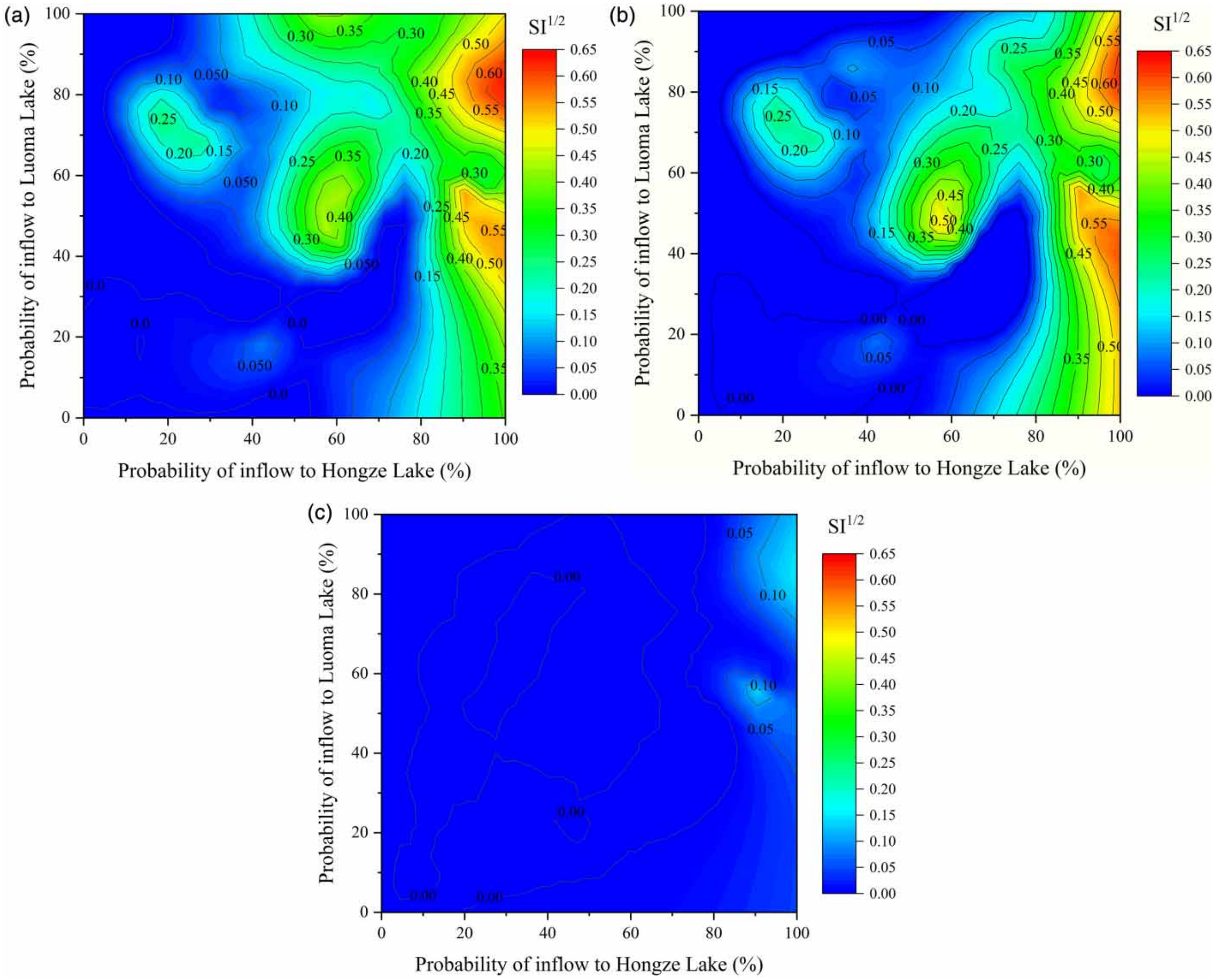

Figure 4 | The water shortage index over the long time series of inflow under different scenarios (contracted amount of annual diverted water from Yangtze River = 7.6 billion m^3). (a) Scenario 1, (b) Scenario 2 and (c) Scenario 3.

Table 3 | The monthly water shortage index under different users and scenarios

User	**User H**			**User L**			**User P**		
Scenario	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Jan	50.3	51.2	12.2	60.1	51.2	12.2	50.3	51.2	12.2
Feb	50.3	51.2	12.2	60.1	51.2	12.2	50.3	51.2	12.2
Mar	50.3	51.2	12.2	60.1	51.2	12.2	50.3	51.2	12.2
Apr	50.3	51.2	12.2	60.1	51.2	12.2	50.3	51.2	12.2
May	50.3	51.2	12.2	60.1	51.2	12.2	50.3	51.2	12.2
Jun	50.3	51.2	12.2	60.1	51.2	12.2	50.3	51.2	12.2
Jul	58.5	58.5	12.2	60.1	58.5	12.2	58.5	58.5	12.2
Aug	60.1	59.9	12.2	60.1	59.9	12.2	60.1	59.9	12.2
Sep	60.1	59.9	12.2	60.1	59.9	12.2	60.1	59.9	12.2
Oct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

4.2. Validation results

To illustrate the effectiveness of the water resource system, the least favorable condition from the time series is chosen as an example. In 1999, a year of extreme drought, the exceedance probability of inflow to both lakes was around 95%. Optimal operation reallocates the water, taking into account the space and time variability of the supply sources: the water shortage index is homogenized in time to avoid periods of intense water shortage, and it is also homogenized in space to guarantee fairness among users. Table 3 lists the monthly water shortage index in 1999 for each category of users under the three different scenarios. The increase of available water resources under scenario 3 results in the water shortage index being decreased to below 20% compared with other scenarios, under which the water shortage index varies between 40 and 60% throughout

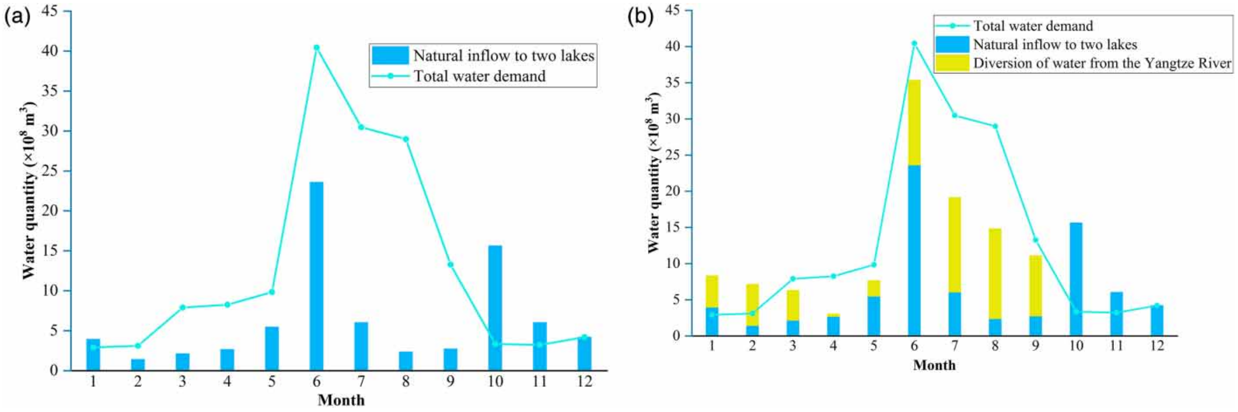

Figure 5 | Monthly natural inflow and diversion of water to the two lakes and water demand. (a) Local water resources (corresponding Scenario 1 and 2). (b) Diverted water from the Yangtze River (corresponding Scenario 3).

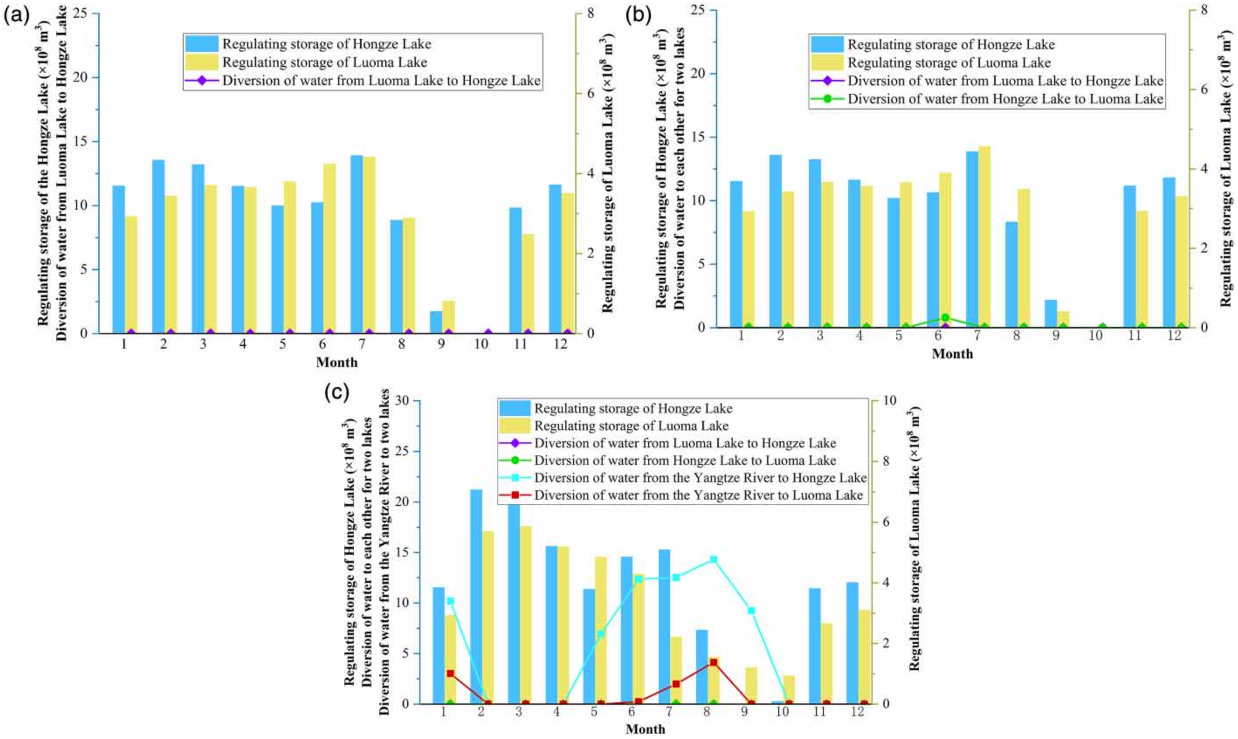

Figure 6 | Monthly water regulating storage and water diversion allocation. (a) Scenario 1, (b) Scenario 2 and (c) Scenario 3.

most of the year. These results thus demonstrate the large impact of the diverted water from the Yangtze River on the water supply. Under scenario 1, when the inflow from the Luoma Lake is reduced, user L faces a serious water shortage issue due to the limited amount of available water resources compared with scenario 2. The water shortage index of user L under scenario 1 is 10% higher than under scenario 2 from January to June. Note how the water scarcity is homogeneously distributed for the different users at all time steps, so that extreme water supply shortage is avoided for every user, thus meeting the requirements of the system. Figure 4 displays the monthly natural inflow and diversion of water to lakes and water demand in 1999 under three different scenarios.

As shown in Figure 5(a), natural inflow cannot meet the demand of water users without replenishment by diversion of water from the Yangtze River, so a serious water shortage issue happens, especially from January to September. As shown in Figure 5(b), water shortage issues can be solved partially through the diversion of a contracted annual volume of water from the Yangtze River. The above conclusion is consistent with the change in the monthly water shortage index in Table 3.

As more water sources than the two lakes and the Yangtze River are involved in the study, the water supply composition is rather complex. The balance between the supply and demand of different users under different scenarios is analyzed in this context. The validity of the water supply modes is further demonstrated from Figure 6, which shows the monthly water storage for each lake as well as the monthly water diversion allocation for each scenario. For scenarios 1 and 2, the change in regulating storage of the Hongze Lake and the Luoma Lake is similar (i.e., the coincidence probability of inflow to the two lakes is high), so that the case of two lakes diverting water from one another does not exist if no water is diverted from the Yangtze River. For scenario 2, a small amount of water is diverted from the Hongze Lake to the Luoma Lake in June, which increases the regulating storage of the Luoma Lake for the next few time intervals. This eases pressure on the water supply of user L and guarantees the fairness of distribution among all users. For scenario 3, the additional water supply source represented by the diversion of water from the Yangtze River greatly increases the available water resources for the water system. It follows the principle of allowing for the water feed to users when the water resource is in shortage, and the replenishment of the lake while the amount of local water is higher than normal. The purpose of diverting water from the Yangtze

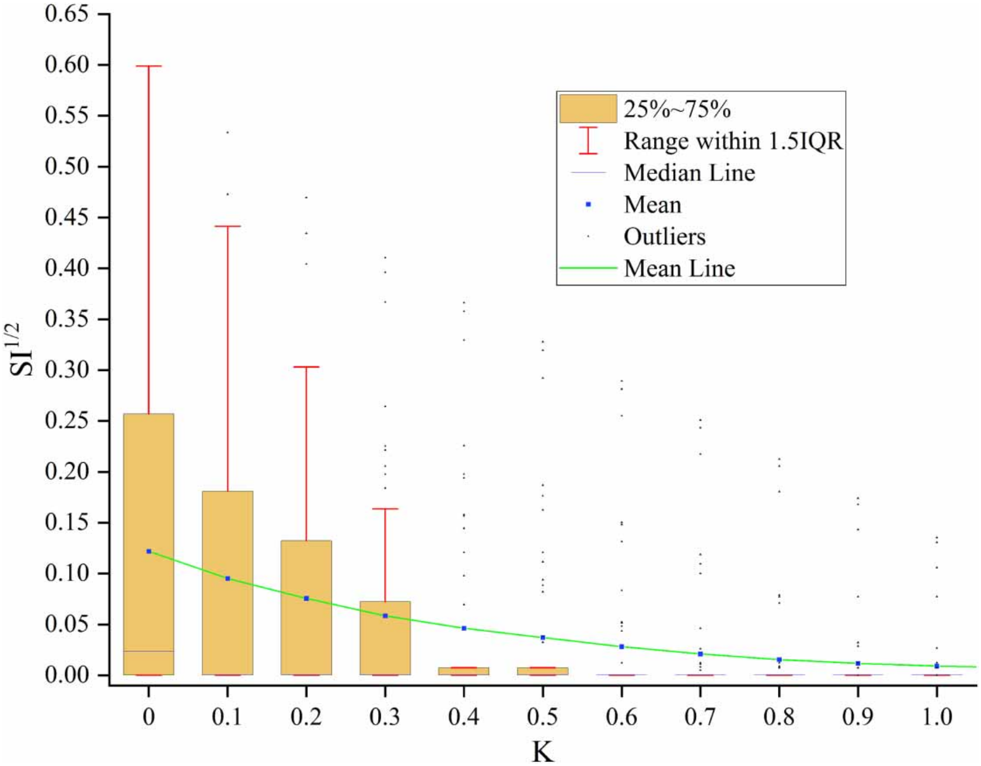

Figure 7 | The water shortage index under conditions set by the long time series flow under different values of annually allowed volume of diverted water *K*. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wcc.2023.259.

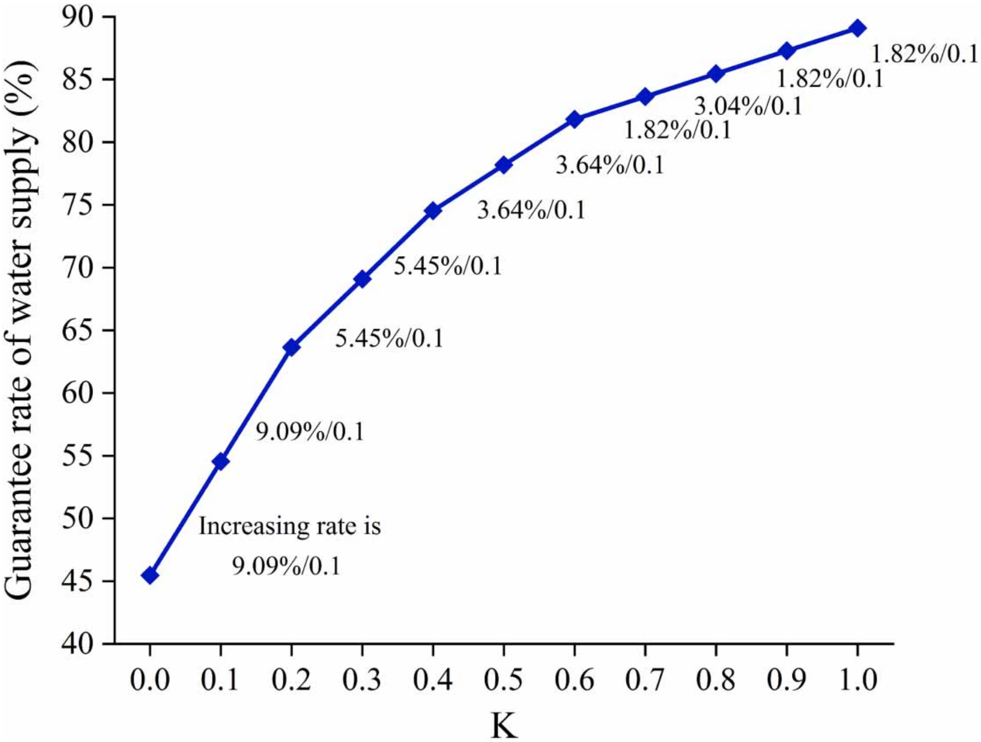

Figure 8 | The water supply reliability under different values of annually allowed volume of diverted water *K*.

River in January is the replenishment of the lakes, which increases their available water for future supply. This guarantees the supply of water for the next time intervals to a certain extent. The amount of diverted water from the Yangtze River is large from June to September, while the regulating storage of the two lakes continues to decline, hence the purpose of diverting water from the river during these months is to guarantee an acceptable water supply.

5. DISCUSSION

As the economic cost of diverting water from the Yangtze River is high, different conditions of the volume of annually diverted water from the Yangtze River are set in order to evaluate and improve the cost-efficiency of the water transfer-supply system.

The different amounts of annually diverted waters from the river are set as different multiples (referred to as *K*) of a contracted value, after which the water balance under different conditions is calculated. The water shortage index is then plotted as a function of the value of *K* in Figure 7. As *K* increases (i.e. increase of the volume of diverted water from the Yangtze River), issues of water shortage in the water resources system improve progressively, as described hereafter: The values of the mean (blue dots and green line), range within 1.5IQR (box) decrease with the increase of *K*, and when *K* exceeds 0.5, the value of the quartiles becomes close to 0, which indicates the transition toward the absence of water shortage.

The reliability of water supply is 78.2% and water shortage index is 2.8% when *K* increases to 0.6, which indicates that water shortage does not occur during most of the long time series, and shows the effect of the diverted water on the water supply. For $K = 1$, the annual diverted water from the Yangtze River reaches the contracted value, the water supply reliability is 89.1% and water shortage index is 0.9%. The reliability of water supply is plotted as a function of the value of *K* in Figure 8. As *K* increases, reliability of water supply increases progressively, but the increasing rate of that decrease. When *K* increases to 0.6, the increasing rate stabilizes on a small value. Therefore, we propose that a value of $K = 0.6$ is a reasonable compromise which allows for the continuity of water supply to the users in almost all cases while limiting the cost of water transfer.

6. CONCLUSIONS

The optimized operation of an inter-basin water transfer system is an effective way to address the uneven distribution of regional water resources. A multi-scenario optimization model for the operation of an inter-basin water transfer-supply system is proposed in this paper to obtain a water transfer scheme that balances the cost–benefit relationship. The proposed method is applied to a real case for optimized operation of the eastern route of the South-to-North Water Diversion Project in China. The findings can be concluded as follows:

1. When the probability of exceeding the standard flow to the Hongze Lake is less than 50% and the probability of exceeding the standard flow to the Luoma Lake is less than 40%, the local water from the Hongze Lake and the Luoma Lake can meet the water demand of the users and there is no need to transfer water across the basin. When the Hongze Lake and the Luoma Lake are at low flows, the impact of water shortage conditions is more sensitive for the Hongze Lake than for the Luoma Lake.
2. With the diversion of a contracted annual volume of water from the Yangtze River, the water supply reliability is 89.1% and the water shortage index is 0.9%. In extreme drought years, the water shortage index can be controlled to within 5 and 10%.
3. When water is diverted from the Yangtze River at 60% of the annual contracted volume, the reliability of the water supply is 78.2% and the water shortage index is 2.8%, which is a compromise between balancing the water shortage index and water transferring volume regarding the cost of water transferring.

AUTHORS CONTRIBUTION

Conceptualization: M.C., B.X., L.W.; Methodology: M.C., W.L., Y.Z.; Formal analysis and investigation: M.C., W.L., Y.Z.; Writing – original draft preparation: M.C.; Writing – review and editing: M.C., Y.Z., L.W., W.L.; Funding acquisition: L.W., B.X., Y.Z., W.L.; Resources: L.W., B.X.; Supervision: L.W.

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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.

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