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The Optimal Operation of Parallel Pumping Stations for Inter-Basin Water Transfer Based on the Multi-Objective Optimization of a Single Pumping Station

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Abstract: A nonlinear mathematical model for the optimal operation of a parallel pumping station group was established with the objective of minimizing the operation costs of the station group considering the target quantity of water extraction and flow unevenness between units of each station as constraints. The original model is decomposed into several sub-models with a single station multi-objective optimization operation with the target water lifting capacity of a single pump station as the coordinating variable. This constructed model was solved using a large-scale system decomposition dynamic programming aggregation method based on sub-system multi-objective genetic algorithm optimization. Taking the Jiangdu parallel pumping station group in the Chinese East Route of the South-to-North Water Diversion Project as a case study, the results show that under the condition of 80% water lifting load of parallel stations and 7.8 m daily average lift, the unit water lifting cost of the optimal operation of each station decreases by 4.81%, 4.81%, 19.83% and 11.06% compared with the constant speed operation at the specified angle. The unevenness of the flow of each station is 2.16 m^3/s, 2.16 m^3/s, 0.60 m^3/s and 14.10 m^3/s. The erosion of the outlet pool is small. This article provides theoretical reference for the optimal operation of the same type of large-scale inter-basin water transfer parallel pumping station groups.

Keywords: pumping station group; minimizing optimization; decomposition dynamic programming aggregation; multi-objective; unevenness

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1. Introduction

Parallel pumping station groups play an important role in inter-basin water transfer projects containing multiple large-scale lifting pumping stations in parallel [1,2]. As a component of a group of parallel pumping stations, single large-scale pumping stations are distinctive for their multiple installed pump units, and their large flow per unit, long running time and high water-lifting cost. During the operating processes of a parallel pumping station group, it is important to take into account the stability and safety of the operation of each station so that the pre-set water transfer target can be achieved.

At present, domestic and foreign research on the optimal operation of inter-basin water transfer pumping stations (groups) has been carried out, most of which aims to minimize the energy consumption of pumping stations (groups) for optimal operation [3–5] or investigates the processes of solving complex parallel or cascade pumping station group optimization models. The decomposition and coordination method [6], genetic algorithm [7], wolf swarm algorithm [8] and ant colony algorithm [9] have been widely applied in solving complex optimization models of parallel or cascade pumping station groups. Edson et al. proposed an optimization algorithm based on dynamic programming that was easy to program, effectively improving the operating efficiency of the pump unit and achieving energy saving [10]. Wang et al. aimed at finding the lowest electricity cost of the water pump operation and took the time-varying electricity price as a consideration [11], selecting the quantity of pumps running in each pumping station as the decision variable to construct the optimal operation model of an urban water pipeline network pumping station, which was solved using integer programming. The results showed that the model has obvious economic benefits.

In the multi-objective optimization operation of pumping stations, most scholars regard the economic efficiency of the operation of the pumping station and the overall safety of the system as study objectives and generally choose intelligent algorithms based on the Pareto optimal solution to solve multi-objective problems. Liang et al. established a multi-objective optimization model with the goal of minimizing the pumping electricity charge and the minimal quantity of unit starts of a pumping station group [12]; this was solved using a hybrid particle swarm optimization algorithm based on the Pareto optimal solution. The results showed that blindly focusing on the economic operation of the pumping station may increase the quantity of unit starts and stops, thus increasing the maintenance costs of the pumping station. Perea et al. constructed a multi-objective optimization model of an irrigation pumping station with minimal water-lifting amounts in the irrigation season and minimal water-lifting costs [13]. A multi-objective genetic algorithm was used to solve the problem, and the water-saving and energy-saving effects reached 25% and 54%, respectively. Jung et al. constructed a multi-objective optimization model with the objective of minimizing the operating cost of a pumping station [14], optimizing the robustness of the nodes of the water supply network system; they also discussed the Pareto relationship between the two objectives. In addition, some scholars have applied the multi-objective optimization algorithm based on the Pareto optimal solution to the optimal layout of a water conservancy project construction site [15] and to the efficient allocation of water resources [16,17].

Relevant studies have shown that during the optimization operations of large-scale inter-basin water transfer pump stations, the pump units frequently change angle and speed: They start and stop, and the flow difference between the units is large. During operation, serious wall erosion in the outlet pool of the pump station is often observed, which has an impact on the safe and stable operation of the pump units. Most existing studies regard the minimum cost or energy consumption in the operation cycle of the pump station as a single objective. Although a calculated operation scheme can play an efficient role in saving energy and reducing the operation cost of a pump station, for a complex single pump station system, we must consider safety during operation. Similarly, for a parallel pumping station group with multiple pumping stations, the operation of each single pumping station should not only be carried out with the goal of economic and efficient operation but should also fully consider the impact of water flow on the outlet pool during operation, and take into account the requirements of safety and stability.

Based on existing research on the multi-objective optimal operation of single pumping stations [18], this article will explore the construction of a complex mathematical model for the optimal operation of a parallel pumping station group and propose the corresponding system engineering solution method to determine the optimal operation schemes. The obtained research results have important theoretical and practical significance for the overall economic and safe operation of inter-basin water transfer pumping station groups.

2. Model Construction

2.1. Objective Function

The objective function of this model is to minimize the total operating electricity cost of the parallel pumping stations during their entire operating period:

$$G = \min\sum_{k=1}^{BZ} F_k(W_k) = \min\sum_{k=1}^{BZ}\sum_{i=1}^{N}\sum_{j=1}^{M} \frac{\rho \cdot g \cdot Q_{k,i,j}\left(\theta_{k,i,j}\right) \cdot H_{k,i}}{\eta_{k,i,j}\left(\theta_{k,i,j}\right) \cdot \gamma_{k,j} \cdot \sigma_{k,j}} \cdot T_i \cdot P_i \tag{1}$$

where G is the minimal power consumption cost of the parallel pumping station group during the given water diversion period (CNY); BZ is the quantity of pumping stations included in the parallel pumping station group; k is the pumping station number (k = 1, 2, 3, . . . , BZ);

$F_k(W_k)$ is the operation cost of the k-th pumping station under actual water extraction W_k (CNY); N is the quantity of time periods divided during a given diversion period; i is the divided time period number (i = 1, 2, 3, ... , N); M is the quantity of pump units in a single pumping station; j is the unit number (j = 1, 2, 3, ... , M); $Q_{k,i,j}(\theta_{k,i,j})$ and $\eta_{k,i,j}(\theta_{k,i,j})$ are, respectively, the flow (m^3/s) and pump efficiency of the j-th unit of the k-th parallel pumping station in the i-th time period corresponding to blade angle $\theta_{k,i,j}$; $H_{k,i}$ is the time-averaged head (m) of the i-th period of the k-th pumping station; T_i and P_i are, respectively, the period length (h) and peak–valley electricity price (yuan/(kW·h)) of the i-th period; γ_j is the motor efficiency of the j-th pump, which can be considered 94% [19] when the load is more than 60%; σ_j is the transmission efficiency of the j-th pump, which can be taken as 100% [20], considering the motor is directly connected to the water pump.

2.2. Constraint Conditions

(1) Target water extraction constraint of the parallel pumping stations:

$$\sum_{k=1}^{BZ} V_k(W_k) = \sum_{k=1}^{BZ}\sum_{i=1}^{N}\sum_{j=1}^{M} Q_{k,i,j}\left(\theta_{k,i,j}\right)\cdot T_i \geq V_e \tag{2}$$

(2) Constraints of flow unevenness of each unit in each pumping station:

In this article, the flow unevenness of a pump unit in each divided time period is defined as the ratio of the absolute difference between the unit flow and average unit flow in the pumping station in that period to the quantity of units. Thus, the flow unevenness of the k-th pumping station under the target pumping capacity of W_k is shown as follows:

$$S_k(W_k) = \sum_{i=1}^{N}\sum_{j=1}^{M} \frac{\left|Q_{k,i,j}\left(\theta_{k,i,j}\right) - \overline{Q}_{k,i}\right|}{M_k} \leq S_{k,0} \tag{3}$$

(3) Motor power constraint:

$$N_{k,i,j}(\theta_{k,i,j}) \leq N_{k,0,j} \tag{4}$$

(4) Unit start–stop times constraint:

$$D_{k,j} \leq D_{k,0,j} \tag{5}$$

where W_k is the target water volume (m^3) of the k-th pumping station during a given water diversion period; $V_k(W_k)$ is the actual pumping capacity (m^3) of the k-th pumping station under the target water volume W_k; V_e is the total target volume of parallel pumping stations (m^3); $S_k(W_k)$ is the flow nonuniformity (m^3/s) of the k-th pumping station under the target pumping capacity W_k; $\overline{Q}_{k,i}$ is the average flow rate (m^3/s) of each pump unit for the i-th period of the k-th pumping station; $N_{k,i,j}(\theta_{k,i,j})$ is the actual motor power (kW) of the j-th pump unit corresponding to the blade angle $\theta_{k,i,j}$ in the i-th period of the k-th pumping station, which should be less than or equal to the motor supporting power $N_{k,0,j}$. $D_{k,j}$ is the quantity of intermittent shutdowns during the operation period of the j-th pump of the k-th pumping station. Considering the large loss of pump units caused by frequent start-ups and shutdowns of large-scale pump units, this should be less than the quantity of intermittent shutdowns specified by each unit $D_{k,0,j}$. $S_{k,0}$ is the maximal constraint value (m^3/s) of flow unevenness of the pumping station, which is determined according to the actual working condition of the pumping station.

3. Model Solution Method

3.1. Decomposition of Large System Model

Taking water extraction W_k of each pumping station in a given time period as the coordination variable and considering the importance of flow non-uniformity constraint of each pump unit in the original model in the safe, stable and durable operation of a pump unit, Equations (1)–(5) could be decomposed into the BZ optimal operation sub-models of a single pumping station with a fully regulated blade.

When the large-scale system is decomposed, due to the influence of the peak–valley electricity price, there is a certain restrictive relationship between flow unevenness of each station and minimal water-lifting cost of each station. Previous research [18] has shown that the smaller the cost, the greater the flow unevenness and vice versa. If the flow unevenness constraint is directly used as the constraint of the decomposed subsystem, the constraint is overemphasized in the subsystem optimization process, which would make the optimization results unsatisfactory [21]. That means that the obtained objective function value of the subsystem is often located at the constraint boundary and the flow unevenness of the pumping station is related to the performance of the unit itself; the subjectively selected upper limit may not be representative. Considering that the optimization method based on the Pareto optimal solution will not be affected by subjective ideas in multi-objective optimization, the frontier of multi-objective optimization can be obtained. By selecting a set of solutions closest to the ideal solution after normalization as the optimal solution, we can effectively take into account the optimization of operating costs and flow inhomogeneity.

In view of the above considerations, this article transformed the flow unevenness constraint in the large system optimization model into the minimal target flow unevenness between pumping stations and units in the subsystem model. In other words, each sub-model took the minimal electricity consumption cost of the pumping station operation during a water transfer period and the minimal water flow unevenness among pump units in the station during each divided time period of the water transfer period as the multi-objectives; the blade angle of each pump unit in each time period was considered as the decision variable; and the total amount of water pumped by the pumping station during the water-lifting period, the supporting power of each motor, and the start and stop requirements of each unit were considered as constraints. The constructed multi-objective mathematical sub-model is as follows:

(1) Objective function 1 (minimal operating cost target of single pumping station):

$$f_1 = \min F_k(W_k) = \min \sum_{j=1}^{M} \sum_{i=1}^{N} \frac{\rho \cdot g \cdot Q_{i,j}(\theta_{i,j}) \cdot H_i}{\eta_{i,j}(\theta_{i,j}) \cdot \gamma_j \cdot \sigma_j} \cdot T_i \cdot P_i \tag{6}$$

(2) Objective function 2 (minimal objective of unit flow unevenness in each period):

$$f_2 = \min S_k(W_k) = \min \sum_{i=1}^{N} \sum_{j=1}^{M} \frac{\left| Q_{k,i,j}(\theta_{k,i,j}) - \overline{Q}_{k,i} \right|}{M_k} \tag{7}$$

(3) Constraint conditions:

① Target water withdrawal constraints:

$$V_k(W_k) = \sum_{j=1}^{M} \sum_{i=1}^{N} Q_{i,j}(\theta_{i,j}) \cdot T_i \geq W_k \tag{8}$$

② Motor power constraint:

$$N_{i,j}(\theta_{i,j}) \leq N_{0,j} \tag{9}$$

③ Quantity of start–stop constraints:

$$D_j \leq D_{0,j} \tag{10}$$

where f_1 is the minimal power consumption cost of a pumping station group during the given water diversion period (CNY); f_2 is the minimal flow unevenness of each pump unit in each period during the primary water transfer period of the pumping station (m^3/s);

$Q_{i,j}(\theta_{i,j})$ and $\eta_{i,j}$ $(\theta_{i,j})$ are, respectively, the flow (m^3/s) and pump efficiency of the j-th unit of the i-th time period corresponding to blade angle $\theta_{i,j}$; H_i is the time-averaged head (m) of the i-th period; D_j is the quantity of intermittent shutdowns during the operation period of the j-th pump. Considering the large loss of pump units caused by frequent start-ups and shutdowns of large-scale pump units, this should be less than the quantity of intermittent shutdowns specified by each unit $D_{0,j}$. Other variables are based on the variables of Equations (1)–(5).

3.2. Sub-Model Solving Based on NSGA-II Algorithm

The above sub-model (6)–(10) is a typical multi-objective and multi-constraint complex nonlinear mathematical model. The relationship between two objective functions means the optimal solution is not unique, and it is feasible to apply a multi-objective genetic algorithm (NSGA-II) to solve the corresponding Pareto solution set. Each group of objective function values in the Pareto front is normalized, after which the nearest set of solutions from the normalized ideal point (0,0) is selected as the best operation scheme, as in expressions (11)–(13):

$$\Delta f_s = \max\left\{f_{s_1}, f_{s_2}, \ldots f_{s_{pop}}\right\} - \min\left\{f_{s_1}, f_{s_2}, \ldots f_{s_{pop}}\right\} \tag{11}$$

$$m_s = \min\left\{f_{s_1}, f_{s_2}, \ldots f_{s_{pop}}\right\} \tag{12}$$

$$\Delta = \left[\sum_{s=1}^{2}\left(\frac{f_{s_p} - m_s}{\Delta f_s}\right)^2\right]^{\frac{1}{2}} \tag{13}$$

where Δf_s is the difference between the maximum and the minimum of the s-th objective in the Pareto front; m_s is the minimum of the s-th objective in the Pareto front; Δ is the distance between each point in the Pareto front and the ideal point after normalization.

Substituting each group of solutions in the Pareto front into the Formulas (11)–(13), when Δ reaches the minimum, the corresponding blade placement angle of each period is the best operation scheme.

This solution method is detailed in previous research [18]. In this article, the penalty function method is used to deal with the constraints of the sub-model.

Within the range of the water-lifting capacity of a given water-lifting head of the subsystem, the target water-lifting amount W_k of subsystem was discrete and a series of sub-model optimizations corresponding to each water-lifting quantity were carried out for each discrete target water-lifting quantity of the subsystem. For each determined target water extraction quantity, a unique optimal operation scheme for a single pumping station and its corresponding actual water extraction quantity $V_k(W_k)$, water extraction cost f_1 and flow unevenness f_2 could be obtained by solving the sub-model.

3.3. Dynamic Programming Aggregation of Large-Scale System

Using the sub-model solution based on the NSGA-II algorithm above, a series of W_k-$V_k(W_k)$, $F_k(W_k)$, $S_k(W_k)$ relations could be obtained, after which the original model (1)–(5) can be transformed into the following large-scale system aggregated model:

3.3.1. Objective Function of Large-Scale Aggregated Model

The objective function of large-scale aggregation model is to minimize the operation cost of parallel pumping stations:

$$G = \min\sum_{k=1}^{BZ} F_k(W_k) \tag{14}$$

3.3.2. Constraint Conditions of Large-Scale Aggregated Model

(1) The target water extraction constraint of parallel pumping stations:

$$\sum_{k=1}^{BZ} V(W_k) \geq V_e \tag{15}$$

(2) Constraints of flow unevenness of each unit in each pumping station:

$$S_k(W_k) \leq S_{k,0} \tag{16}$$

(3) Motor power constraint and unit start–stop times constraint Formulas (4) and (5).

The above aggregated model (11)–(15) is a typical one-dimensional dynamic programming with pumping station number k (k = 1, 2, . . . , BZ) as the stage variable and the target water extraction quantity W_k of each station in a water extraction period as the decision variable. W_k was discrete within the allowable water extraction amount range of the pumping station, which was solved using a one-dimensional dynamic programming method. In the actual solution process, the discrete step size of the decision variable could be selected to be consistent with the discrete step size of the target water lift in the sub-model solution, which can reduce the runtime without affecting the accuracy of the model solution.

After obtaining the best combination of water-lifting capacity of each station, the optimal operation scheme of each unit of each station could be checked according to the results of the sub-model optimization. Finally, the optimal distribution results of water volume among stations could be obtained, as shown in Figure 1.

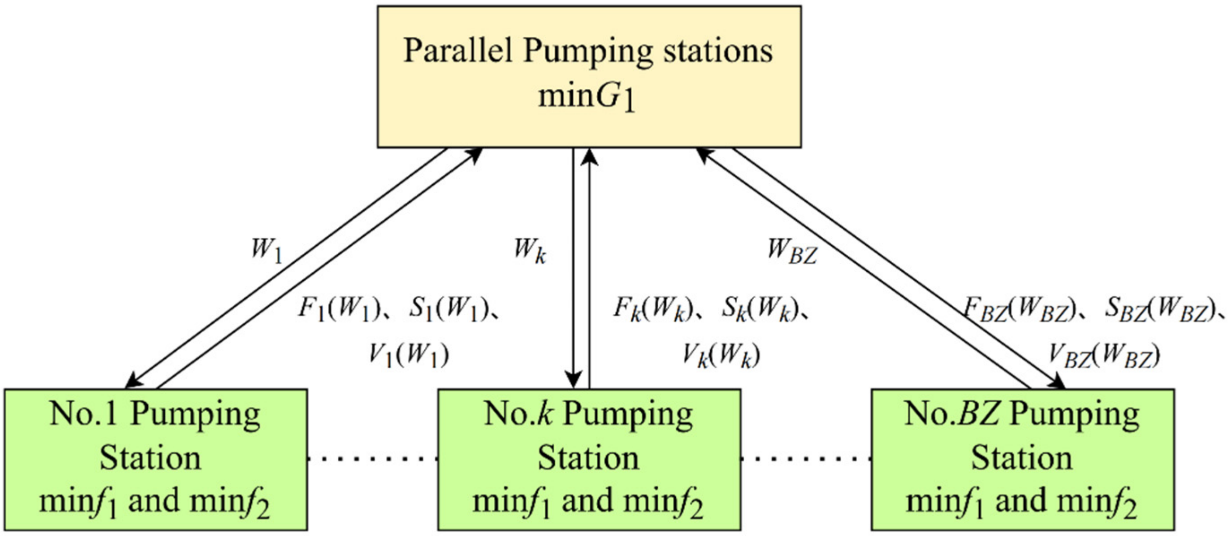

Figure 1. Schematic diagram of subsystem aggregation.

4. Analysis of Case Study

4.1. Jiangdu Parallel Station Group

The Jiangdu parallel pumping station group, which is a source pumping station project of the Eastern Route of the South-to-North Water Diversion Project, is located in Yangzhou City, Jiangsu Province, China. It has four single pumping stations: Jiangdu No. 1, No. 2, No. 3 and No. 4 (Figure 2). Specific information on the parameters of each pumping station [22] is shown in Table 1.

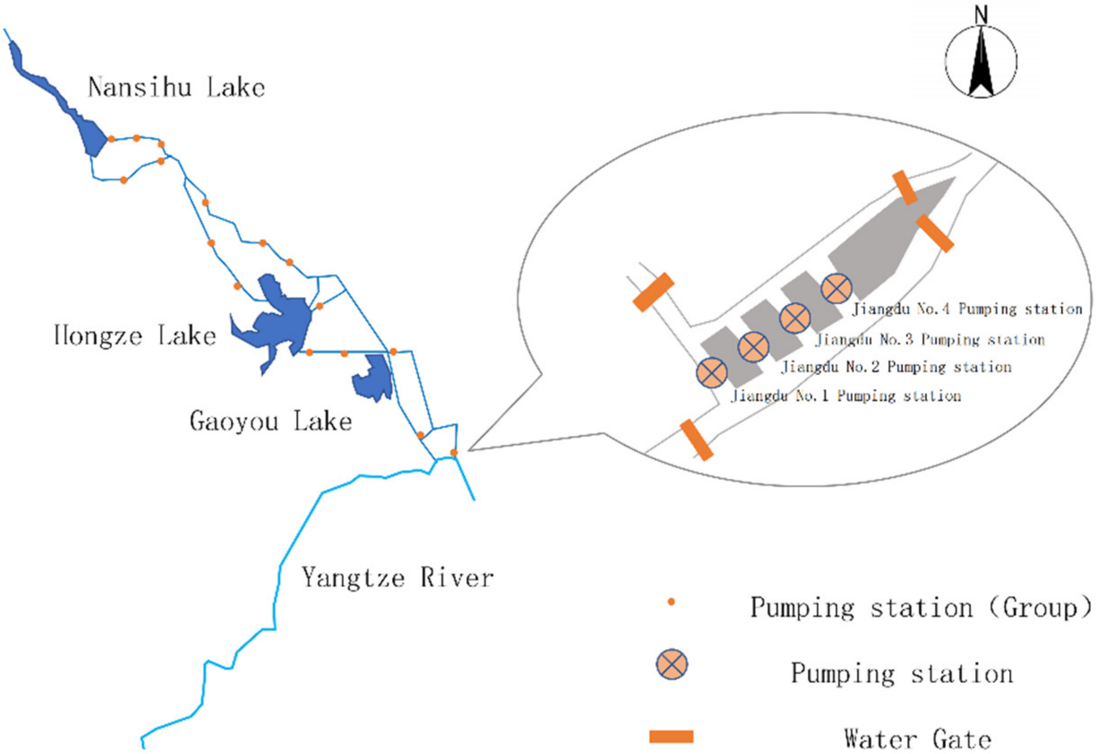

Figure 2. Jiangdu parallel pumping station group geographical location and layout.

Table 1. Basic information on the Jiangdu parallel pumping station group.

Name of Pumping Station	Jiangdu No.1 Pumping Station	Jiangdu No.2 Pumping Station	Jiangdu No.3 Pumping Station	Jiangdu No.4 Pumping Station
Quantity of installed pump units	8	8	10	7
Pump model	1.75ZLQ-7	1.75ZLQ-7	2000ZLQ13.7-7.8	3000ZLQ33.0-7.8
Rated speed (r/min)	250	250	214.3	150
Rated motor power (kW)	1000	1000	1600	3400
Design head (m)	6.0	6.0	7.8	7.8
Range of head (m)	[3.5, 8.5]	[3.5, 8.5]	[3.2, 9.0]	[3.5, 8.5]
Designed blade angle (°)	0	0	+2	0
Regulation range of blade angle (°)	[−4, +4]	[−4, +4]	[−4, +4]	[−4, +4]

Considering the workload of the optimization calculation, the discrete step sizes of the blade angles for each pumping station are taken as 2° in the optimization solution. With the consideration of the influence of time on the length of the entire water extraction period, the upper quantity of shutdowns during daily operation of a single unit is taken as two [23]. According to the change in the average daily tide level in the Yangzhou section of the Yangtze River and the current peak–valley electricity price, the entire water pumping period is considered as one day divided into nine periods. The average head of each period and the combination of peak–valley electricity price are shown in Figure 3 and Table 2 [18].

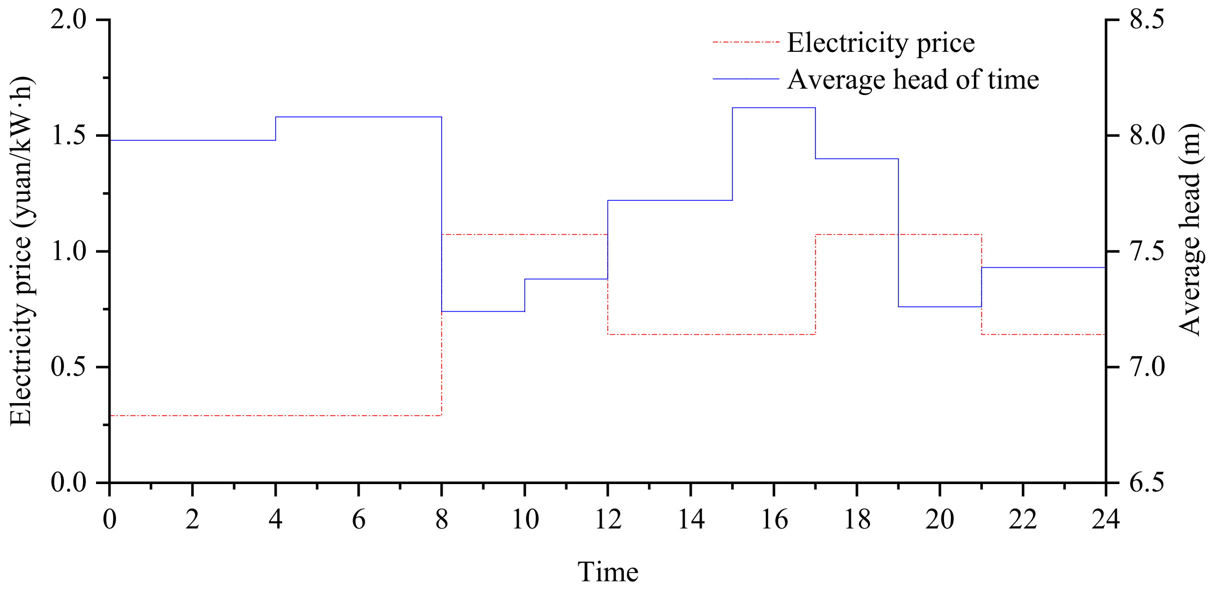

Figure 3. Combined schematic diagram of peak–valley electricity price and time-averaged head of the Jiangdu parallel pumping station group under an average daily head of 7.8 m.

Table 2. Electricity price of each time period and corresponding hourly average lift when the average daily lift is 7.8 m.

Time Period	Duration (h)	Electricity Price (yuan/kW·h)	Average Head of Time (m)
Time period 1 (17:00–19:00)	2	1.0724	7.90
Time period 2 (19:00–21:00)	2	1.0724	7.26
Time period 3 (21:00–24:00)	3	0.6414	7.43
Time period 4 (00:00–04:00)	4	0.2904	7.98
Time period 5 (04:00–08:00)	4	0.2904	8.08
Time period 6 (08:00–10:00)	2	1.0724	7.24
Time period 7 (10:00–12:00)	2	1.0724	7.38
Time period 8 (12:00–15:00)	3	0.6414	7.72
Time period 9 (15:00–17:00)	2	0.6414	8.12

The optimal starting time of a pumping station affected by the tide was studied in previous research [1], which showed that the optimal starting time mainly depends on the beginning time of the rising tide. Therefore, in our calculation, the starting time of the water extraction period is taken as 17:00, which is the beginning time of the rising tide in one day.

4.2. Engineering Example Solution and Analysis

Considering that Jiangdu No. 3 and No. 4 stations play a major role in the Jiangdu parallel pumping station group, the design head of 7.8 m was selected as the typical average daily head of the parallel pumping station group. Taking into account the reliability of the pumping station group during operation, one unit in Jiangdu No. 3 was selected as the standby unit, and the remaining units were optimized for operation calculation.

According to the definition of 100%, 80% and 60% water-lifting loads of pumping stations from previous research [24], the corresponding three kinds of water-lifting loads of the Jiangdu parallel pumping station group studied in this article at the average daily operation head of 7.8 m are 4419.58×10^4 m^3, 3535.66×10^4 m^3 and 2651.75×10^4 m^3, respectively. Detailed information is shown in Table 3.

Table 3. Target water extraction of each pumping station under different kinds of water extraction loads with average daily head of 7.8 m.

Name of Pumping Station	Water Extraction at Different Loads (10^4 m^3)		
	100% Load	80% Load	60% Load
Jiangdu No.1 Pumping Station	591.20	472.96	354.72
Jiangdu No.2 Pumping Station	591.20	472.96	354.72
Jiangdu No.3 Pumping Station	1172.18	937.74	703.31
Jiangdu No.4 Pumping Station	2065.00	1652.00	1239.00
Summation	4419.58	3535.66	2651.75

Considering the workload of the optimization calculation, the discrete step sizes of the target water lifting capacity of each station were set as 7.5×10^4 m^3, 7.5×10^4 m^3, 26.58×10^4 m^3 and 35×10^4 m^3. For each discrete water-lifting load of each station, sub-model optimization based on the NSGA-II algorithm was applied separately to calculate the optimal operation scheme. Considering that Jiangdu No. 1 and No. 2 had the same structure, quantity and model of units, only one of the pumping stations needs to be optimized in the process of sub-model optimization. After all sub-model optimization was completed, the water-lifting cost $F_k(W_k)$ and the flow unevenness $S_k(W_k)$ under different target water extraction requirements of each pumping station could be obtained. Taking the 80% load target water extraction as an example, the minimal water extraction cost and corresponding flow unevenness of the pumping station group are shown in Table 4.

Table 4. Optimization results of a large-scale system aggregated model under daily head 7.8 m with 80% water extraction load.

Name of Pumping Station	Target Water Extraction (10^4 m^3)	Actual Water Extraction (10^4 m^3)	Power Cost (10^4 CNY)	Flow Unevenness (m^3/s)
Jiangdu No.1 Pumping Station	482.5	482.65	8.41	2.16
Jiangdu No.2 Pumping Station	482.5	482.65	8.41	2.16
Jiangdu No.3 Pumping Station	740.4	741.09	11.79	0.6
Jiangdu No.4 Pumping Station	1858.5	1868.24	31.64	14.1
Totals	3563.9	3574.63	60.25	/

In order to carry out an optimization efficiency comparison, the water lifting cost of conventional operation, which was defined as operation with the designed blade angle and constant rotational speed under average daily head of 7.8 m and 80% load, is shown in Table 5.

Table 5. Conventional operation results under average daily head 7.8 m and 80% water extraction load.

Name of Pumping Station	Target Water Extraction (10^4 m^3)	Actual Water Extraction (10^4 m^3)	Power Cost (10^4 CNY)	Flow Unevenness (m^3/s)
Jiangdu No.1 Pumping Station	472.96	473.07	8.67	/
Jiangdu No.2 Pumping Station	472.96	473.07	8.67	/
Jiangdu No.3 Pumping Station	937.74	1009.64	20.04	/
Jiangdu No.4 Pumping Station	1652.00	1908.80	36.35	/
Totals	3535.66	3864.58	73.73	/

Compared with the conventional operation with the designed blade angle and constant speed under average daily head of 7.8 m with 80% load, with an operation cost of CNY 737,300, the optimal operation under the same conditions saved CNY 134,800. The unit cost of the water pumping quantity per 10^4 m^3 was also reduced from CNY 190.78 to CNY 168.54, accordingly, which was a decrease of 11.66%.

The optimal operation efficiency in water pumping costs compared with the conventional operation of each pumping station is shown in Figure 4, indicating that the unit water-lifting cost of the optimal operation of each station is, respectively, 4.81%, 4.81%, 19.83% and 11.06% lower than that of the conventional operation. Regarding the actual water lifting quantity of each station, on the basis of meeting the target water lifting quantity of the whole parallel pumping station group, the water lifting quantity of Jiangdu No. 1 and No. 2 pumping stations increased by 9.57×10^4 m^3 compared with the conventional operation, but there was a decline in the water lifting quantity of the other two pumping stations. The water volume of Jiangdu No. 3 and No. 4 pumping station dropped from 1009.64×10^4 m^3 and 1908.85×10^4 m^3 in the conventional operation to 741.09×10^4 m^3 and 1868.24×10^4 m^3, respectively, with a decrease of 26.6% and 2.13%.

The unevenness of each pumping station and the corresponding proportion to the design flow under the daily average head of 7.8 m is shown in Figure 5. This shows that the flow unevenness of each station was 2.16 m^3/s, 2.16 m^3/s, 0.60 m^3/s and 14.10 m^3/s, respectively, which accounts for 3.16%, 3.16%, 0.48% and 5.90% of the water flow under the designed blade angle of each station and average daily head of 7.8 m. The unit water lifting cost of the whole parallel pumping station group was significantly reduced, achieving good economic benefits at the expense of a small part of the flow uniformity.

The water extraction of the parallel pumping station group and corresponding peak–valley electricity price in each divided time period are shown in Figure 6, which shows that due to the influence of peak–valley electricity price, the water extraction of the pumping stations had a large fluctuation in each period, which was generally negatively correlated with the electricity price level. Water extraction is mainly concentrated in the third, fourth and fifth time periods of the water extraction period, which accounts for 57.8% of total water extraction in the whole operation period. The flow unevenness of each pumping station in the three periods above (shown in Table 6) was at a low level, which indicated that in the process of large flow water extraction, due to the existence of the flow nonuniformity target in the sub-model, the flow nonuniformity of a pumping station could be maintained at a low level. This is of great significance to the safe operation of pumping stations.

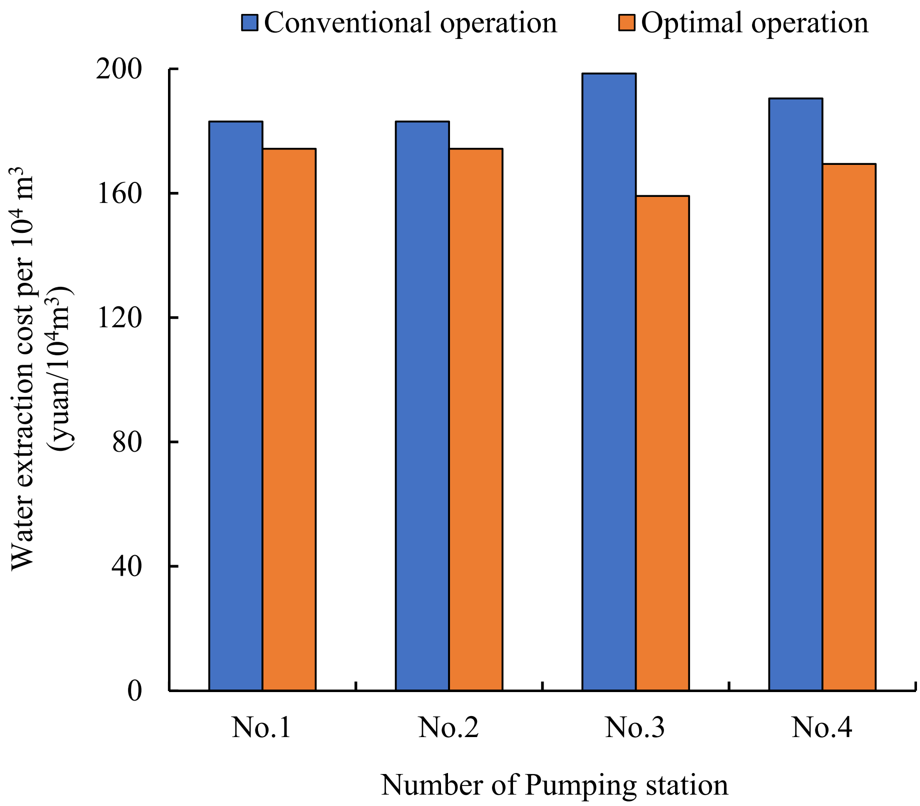

Figure 4. Optimal operation efficiency of water pumping costs compared with conventional operation of each pumping station.

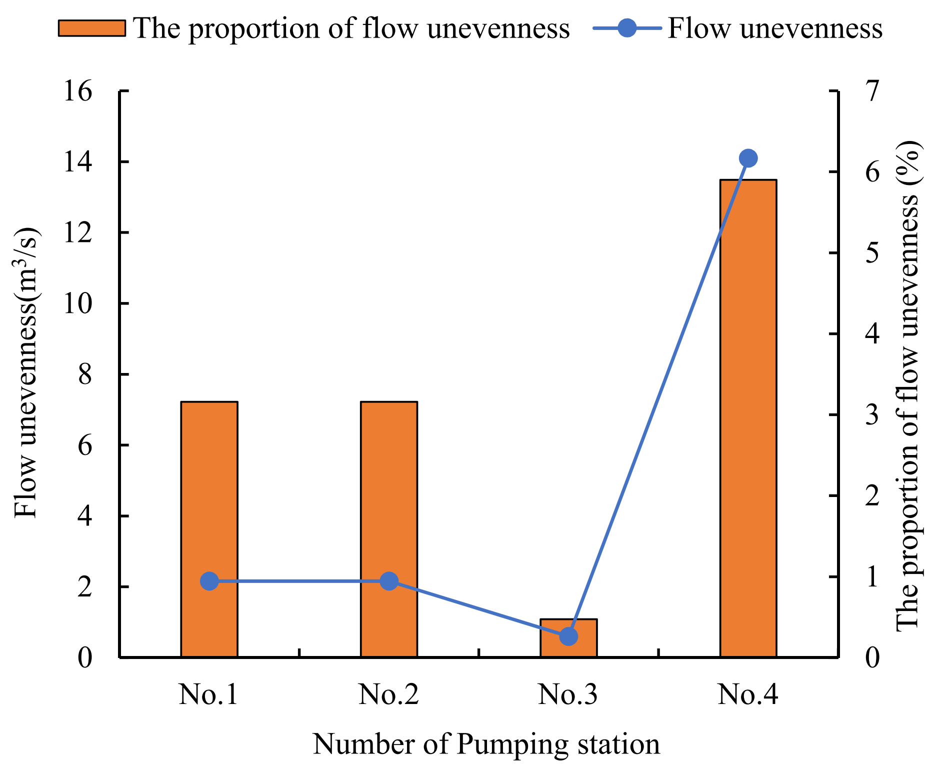

Figure 5. Unevenness of each pumping station and corresponding proportion to the design flow under the daily average head of 7.8 m.

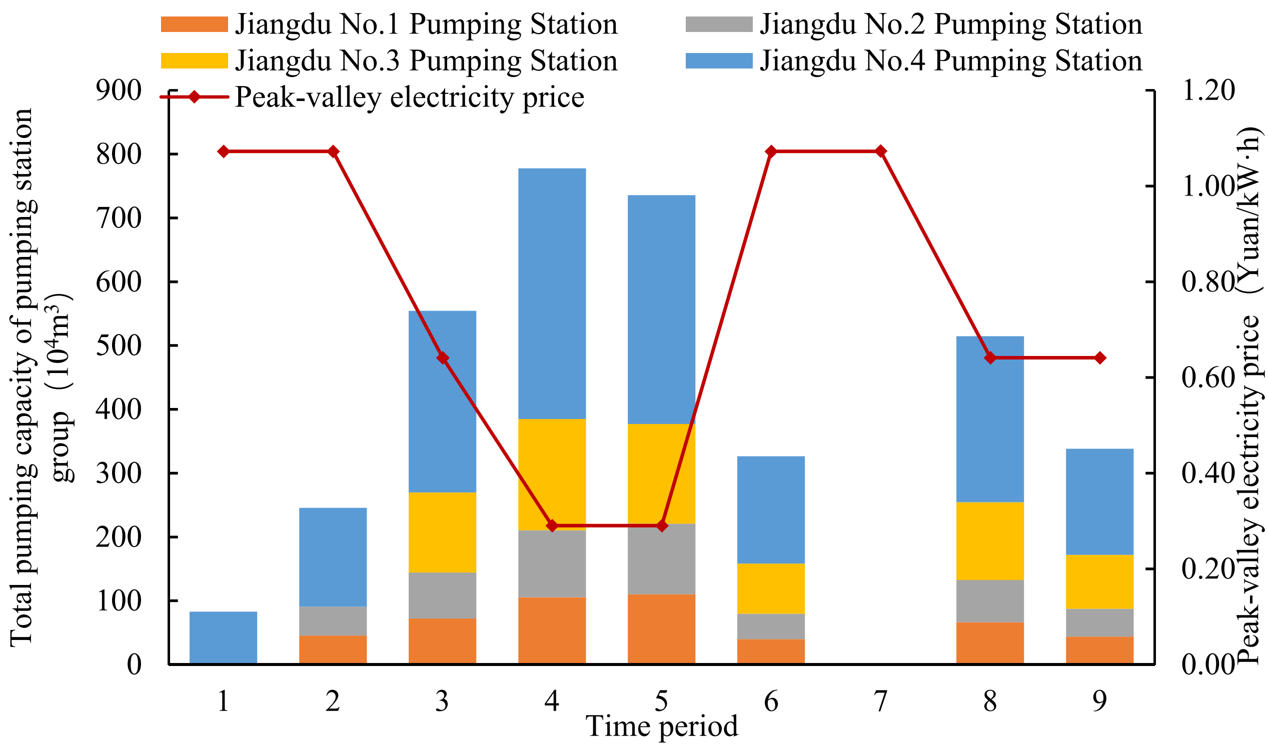

Figure 6. Water extraction of a parallel pumping station and corresponding peak–valley electricity price in each divided time period.

Table 6. Flow unevenness of each pumping station in time periods 3, 4 and 5.

Name of Pumping Station	Flow Unevenness (m^3/s)		
	Time Period 3	Time Period 4	Time Period 5
Jiangdu No.1 Pumping Station	0	0.148	0
Jiangdu No.2 Pumping Station	0	0.148	0
Jiangdu No.3 Pumping Station	0	0.272	0.221
Jiangdu No.4 Pumping Station	0	0	0

According to the recommendations of the *Technical Management Regulations for Pumping Stations (GB/T 30948-2021)*, in the operation of each single pumping station, on the premise of meeting the water supply or drainage plan, the flow state of intake and outlet sump can be improved by optimal scheduling and adjustment of working conditions for pump units in the station, by which the hydraulic erosion and hydraulic loss can be effectively reduced. In an actual operation process, in order to ensure the safe operation of a pumping station during the optimal operation process, it is a low-cost and effective method for arranging pump units with the same water extraction flow symmetrically along the central axis of the pumping station [25]. As a result, the optimal operation scheme of each unit of the pumping station can be revised. After the correction, the optimal operation scheme of each pump unit in the Jiangdu parallel pumping station group under an average daily operation head of 7.8 m with 80% lift load was obtained as shown in Figure 7.

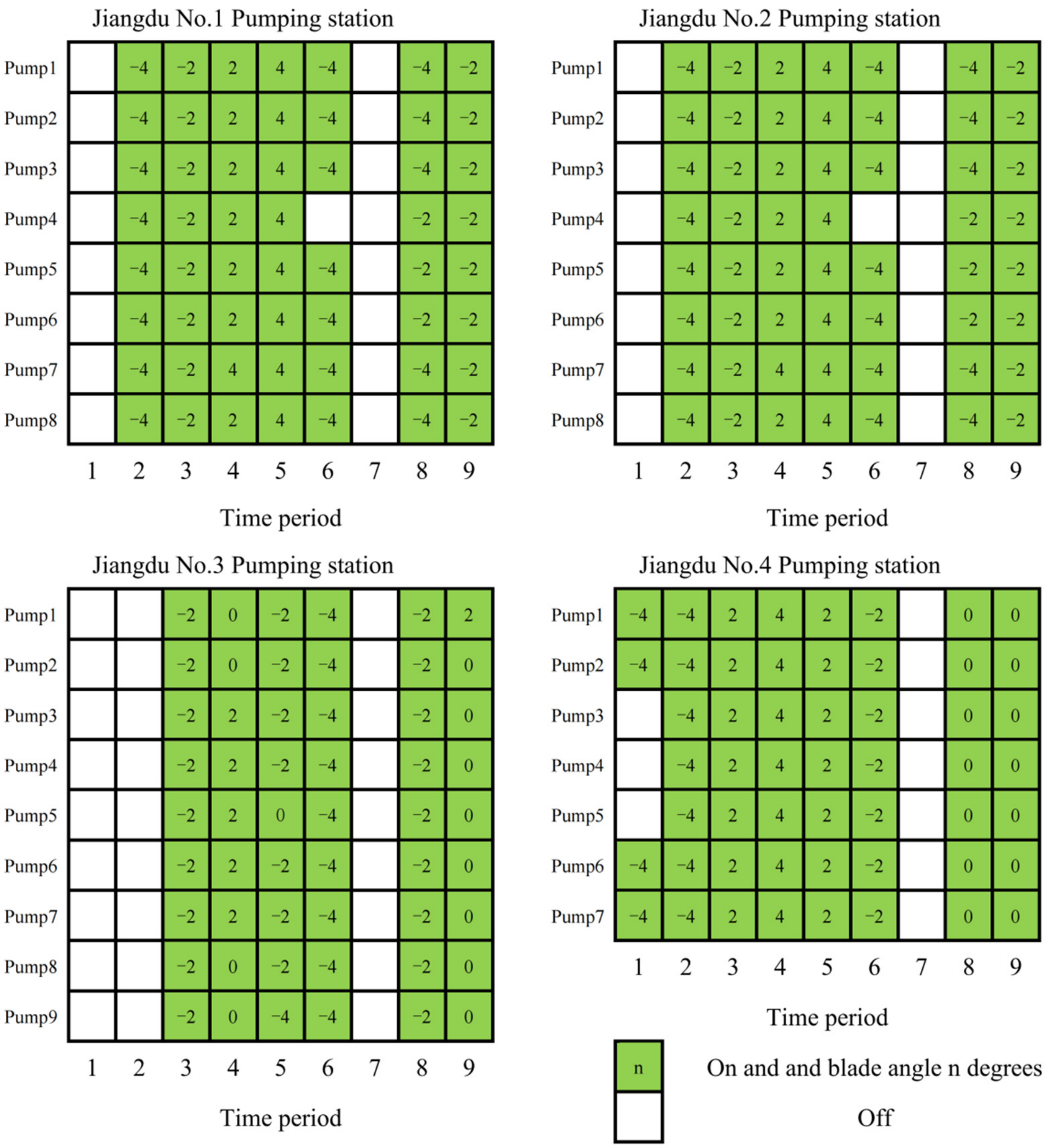

Figure 7. Optimal operation scheme of each pump unit in the Jiangdu parallel pumping station group under an average daily operation head of 7.8 m with 80% lift load.

5. Results and Discussion

Fully considering the operation characteristics of a parallel pumping station group, this article constructed a complex large-scale system optimization mathematical model for the optimal operation of a parallel pumping station group, which was solved using large-scale system decomposition dynamic programming aggregation based on the NSGA-II algorithm and sub-models. In the process of solving the sub-models, the objective of flow unevenness effectively ensured the safety of the pumping station in the operation process and reduced wall erosion and scour flow caused by the flow difference among pump units [26,27].

Compared with the previous sub-model optimization research on a single pumping station in the parallel pumping station group, which generally aimed at finding the lowest single operation cost or energy consumption, the new multi-objective sub-model effectively takes into account the safety of the operation of the pumping station on the premise of meeting the demand for water extraction, and is more conducive to the long-term safe operation of pumping stations. At the same time, since the operation of all units in the pumping station tends to be consistent, the burden of operation management can be greatly reduced and the probability of errors in operation can be reduced.

Taking the Jiangdu parallel pumping station group as a case study, our results showed that the unit water-lifting cost of each single station with optimal operation is 3.16%, 3.16%, 0.48% and 5.90% lower, respectively, than the conventional operation. Under the premise of meeting the constraints of the total amount of water pumping, the actual water lifting quantity of Jiangdu stations 3 and 4 decreased from 1009.64×10^4 m^3 and 1908.85×10^4 m^3 in conventional operation to 741.09×10^4 m^3 and 1868.24×10^4 m^3, respectively, i.e., a decrease of 26.6% and 2.13%. In the meantime, although the flow unevenness of each pumping station increased compared to the conventional operation, the increase was small, which can effectively ensure the long-term safe operation of each pumping station. This research has a certain guidance and reference significance for the operation of parallel pumping station groups with a certain number of large-scale inter-basin water transfer pumping stations. In this paper, the economy and safety of the operation of the pumping station group are considered, but the number of starts and stops of the units in the actual operation of the pumping station will also have a great impact on safety. In this paper, only the number of stops of a single unit in a water lifting cycle was set as a constraint. In the future, in addition to the operation cost of the pumping station and the uneven degree of flow between units, we can consider the impact of the number of unit starts and stops on the operation safety of the pumping station, so that the model is more comprehensive in considering the safety performance.

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