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Optimal water allocation method based on the genetic algorithm for a system of a reservoir and two pumping stations

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ABSTRACT

The subtropical monsoon climate zone features abundant water resources but with uneven temporal and spatial distribution, so seasonal water shortages are frequent. In order to reduce the water shortage and water spill in this region, a nonlinear optimization model for the joint operation of a system of a reservoir and two pumping stations is developed in this paper. In this model, the water supply of the reservoir and pumping volume of the pumping stations in each period are two types of decision variables, which are subjected to the annual available water in the reservoir, water rights of the two pumping stations and the operation rule of the reservoir. However, modern intelligent algorithms may fail in dealing with constraints of if-statements like the operation rule of the reservoir in this model. In light of the shortcoming of the classical genetic algorithm, a modified genetic algorithm is proposed by comparing the different methods for dealing with constraints. The modified algorithm shows a better adaptability to the operation rule. The modified genetic algorithm may provide a reference for similar modern intelligent algorithms to solve optimal water resources allocation for systems of multiple reservoirs and multiple pumping stations.

Key words: genetic algorithm, operation rule, optimal water resources allocation, reservoir

HIGHLIGHTS

- A modified method for the genetic algorithm is proposed to solve the optimal water allocation model for a system of reservoir and pumping stations.
- The method can deal with the constraints of if-statements.
- The method shows a better adaptability to the operation rule of a reservoir, compared with other methods.

1. INTRODUCTION

In recent years, many scholars have conducted research on theories and methods for the optimal water allocation of reservoirs (Taghian *et al.* 2014; Kumari & Mujumdar 2015; Ahmad *et al.* 2018; Khosrojerdi *et al.* 2019; Zarei *et al.* 2019). The dynamic programming method, which has good applicability in multi-stage decision-making processes, has been widely used in the optimization of reservoir operation (Shi *et al.* 2015; Zhao *et al.* 2017; Gong *et al.* 2019; Ma *et al.* 2020). However, dynamic programming may cause the 'curse of dimensionality' in complicated multidimensional problems (Ahmad *et al.* 2014; Yang *et al.* 2016; Ji *et al.* 2017). The genetic algorithm, a typical meta-heuristic algorithm, features outstanding global searching capability and strong robustness (Ngoc *et al.* 2014), so it has been extensively applied in optimizing the operation of reservoirs.

However, the genetic algorithm has shortcomings such as the existence of the premature phenomenon and a slow rate of convergence. Therefore, many scholars have tried to improve this algorithm. An adaptive genetic algorithm with simulated binary crossover was proposed by Han *et al.* (2012). To solve the complex self-adaptive GA (genetic algorithm)-aided multi-objective ecological reservoir operation model, an improved self-adaptive GA (Hu *et al.* 2014) was employed through incorporating simulated binary crossover and self-adaptive mutation. Then an improved nondominated sorting genetic algorithm II (NSGA-II) algorithm was developed by considering variables' sensitivity to improve its search efficiency (Xu & Chen 2020). What is more, it is reported that combined or hybrid genetic algorithm techniques show better results than simply the genetic algorithm (Hossain & El-Shafie 2013). Therefore, the combination of the genetic algorithm and other algorithms is also widely used for the optimal water allocation of reservoirs. Ehteram *et al.* (2017) proposed a new hybrid algorithm by merging the genetic algorithm with the krill algorithm. Azizipour & Afshar (2017) proposed an adaptive hybrid genetic algorithm and cellular automata method for solving implicit stochastic optimization of reservoir operation problems. Rani & Srivastava (2016) proposed the DP–GA (dynamic programming and genetic algorithm) approach, which was found to outperform both GA and DP in terms of lower computational requirement and the quality of the solution, respectively.

At present, the improvements of the genetic algorithm mainly concentrate on modifications of individual coding methods, selection operators, crossover operators and mutation operators, but rarely make efforts in the modification of iterative processes. Moreover, modern intelligent algorithms, such as the genetic algorithm and particle swarm algorithm, have difficulty in solving optimization problems with equality constraints and constraints of if-statements, because of the limit of random sampling (Birhanu *et al.* 2014; SaberChenari *et al.* 2016). However, in an optimization model of a reservoir, the water balance function is a typical equality constraint while the operation rule of the reservoir is a typical constraint of if-statements, both of which are inevitable.

A nonlinear optimization model for the joint operation of a reservoir and two pumping stations was developed in this study for the purpose of minimizing the water shortage. According to the characteristics of this nonlinear optimization model, different iterative procedures with different fitness functions based on the principle of the genetic algorithm were established and compared with each other.

2. METHODOLOGY

2.1. Generalization of the system

The system of a reservoir and two pumping stations is commonly used in the hilly regions of southern China and south-east Asia, which is shown in Figure 1. In the system, the reservoir provides water for the irrigation area and the replenishment pumping station lifts water from the outside river to replenish the reservoir, while the irrigation pumping station lifts water from the inside river directly for irrigation through canals. The conjunctive utilization of local runoff, transit runoff and irrigation return flow can be realized through the joint operation of this system.

In the figure: X_i is the water supply of the reservoir for irrigation in period i, Y_i is the pumping volume of the irrigation pumping station in period i, Z_i is the pumping volume of the replenishment pumping station in period i, YS_i is the water demand of irrigation in period i, LS_i is the inflow of the reservoir in period i, PS_i is the water spill of the reservoir in period i, and EF_i is the evaporation of the reservoir in period i.

2.2. Mathematical model

2.2.1. Objective function

The objective function is to minimize the annual sum of squared water shortage in the system. In the system of a reservoir and two pumping stations, the reservoir and the irrigation pumping station supply water for the irrigation area, so the objective

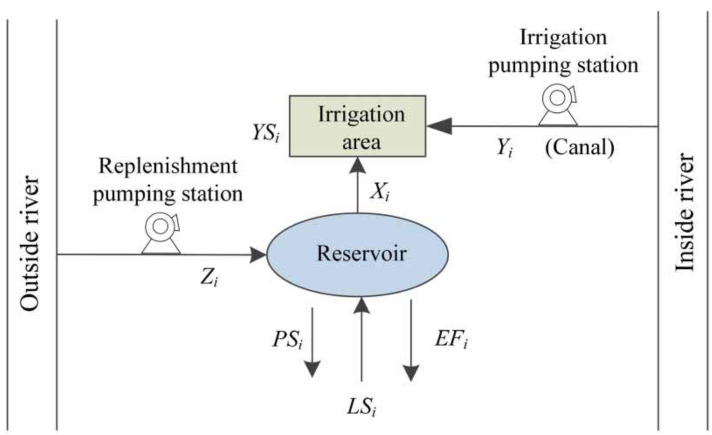

Figure 1 | Generalization of the system.

function can be expressed as Equation (1):

$$\min F = \sum_{i=1}^{N} (X_i + Y_i - YS_i)^2 \tag{1}$$

where F is the sum of the squared water shortage, N is the total number of periods, and i is the period number ($i = 1, 2, \ldots, N$).

2.2.2. Constraints

(1) Annual available water in the reservoir

$$\sum_{i=1}^{N} X_i \leq K + BW \tag{2}$$

where K is the total annual available water of the reservoir, and BW is the water rights of the replenishment pumping station, i.e. maximum annual pumping volume, of the replenishment pumping station.

(2) Water rights of the replenishment pumping station

$$\sum_{i=1}^{N} Z_i \leq BW \tag{3}$$

$$Z_i \leq Z_{i,\max} \tag{4}$$

where $Z_{i,\max}$ is the maximum pumping capacity of the replenishment pumping station in period i.

(3) Water rights of the irrigation pumping station

$$\sum_{i=1}^{N} Y_i \leq BN \tag{5}$$

$$Y_i \leq Y_{i,\max} \tag{6}$$

where BN is the water rights of the irrigation pumping station, i.e. maximum annual pumping volume, of the irrigation pumping station, and $Y_{i,\max}$ is the maximum pumping capacity of the irrigation pumping station in period i.

(4) Operation rule of the reservoir

The water storage of the reservoir in each period should meet the requirements of the lower and upper bounds, which can be expressed as Equation (7):

$$V_{i,\min} \leq V_i \leq V_{i,\max} \tag{7}$$

where V_i is the water storage of the reservoir in period i, $V_{i,\min}$ is the lower bound of water storage in period i, and $V_{i,\max}$ is the upper bound of water storage in period i.

The water storage of the reservoir in each period can be derived according to the water balance equation, which can be written as Equation (8):

$$V_i = V_{i-1} + LS_i + Z_i - X_i - PS_i - EF_i \tag{8}$$

① If $V_i < V_{i,\min}$, then the replenishment pumping station should replenish water to the reservoir and the pumping volume of the replenishment pumping station and water spill of the reservoir in period i can be expressed as

Equations (9) and (10), respectively:

$$Z_i = V_{i,\min} - V_i \tag{9}$$

$$PS_i = 0 \tag{10}$$

② If $V_i > V_{i,\max}$, then excess water should be drained and the pumping volume of the replenishment pumping station and water spill of the reservoir in period i can be expressed as Equations (11) and (12), respectively:

$$Z_i = 0 \tag{11}$$

$$PS_i = V_i - V_{i,\max} \tag{12}$$

③ If $V_{i,\min} \leq V_i \leq V_{i,\max}$, then the water replenishment and spill in period i should both be zero, as Equation (13):

$$Z_i = PS_i = 0 \tag{13}$$

2.3. Genetic algorithm

The genetic algorithm is adopted to solve the above model and the basic procedure is that of generating the initial populations and then carrying out iterative calculations through selection, crossover and mutation operations until the termination criterion is met. In this study, three types of methods to deal with the constraints are compared when using the genetic algorithm, which include the penalty function method, the limited search space method and the modified method proposed in this paper.

2.3.1. Penalty function method

The penalty function method (Knypiński 2019) is to select X_i, Y_i, Z_i and PS_i as iteration variables. The feasible ranges for X_i, Y_i, Z_i and PS_i are [0, YS_i], [0, $YS_i - X_i$], [0, $Z_{i,\max}$] and [0, $LS_i - YS_i$], respectively. This method uses the penalty functions to deal with the constraints, transforming a constrained problem into an unconstrained one. Furthermore, the lower and upper bounds of the water storage of the reservoir in each period should be satisfied by introducing the penalty functions as Equations (14) and (15):

① If $V_i > V_{i,\max}$, then

$$ZP_1 = \sum_{i=1}^{N} (V_i - V_{i,\max})^2 \tag{14}$$

② If $V_i < V_{i,\min}$, then

$$ZP_1 = \sum_{i=1}^{N} (V_{i,\min} - V_i)^2 \tag{15}$$

The constraint of total annual pumping capacity of the two pumping stations in each period should be satisfied by introducing the penalty function as Equations (16) and (17):

$$ZP_2 = \left(\sum_{i=1}^{N} Y_i - BN\right)^2 \tag{16}$$

$$ZP_3 = \left(\sum_{i=1}^{N} Z_i - BW\right)^2 \tag{17}$$

Finally the fitness function can be expressed as Equation (18):

$$F' = \sum_{i=1}^{N} (X_i + Y_i - YS_i)^2 + \sigma \sum_{j=1}^{3} ZP_j \tag{18}$$

where F' is the fitness function, ZP_j is the obstacle function, and σ is the penalty factor.

2.3.2. Limited search space method

The limited search space method (Michalewicz & Schoenauer 1996) is to select X_i, Y_i, Z_i and PS_i as iteration variables as well. Differently, this method restricts the search space to handle the constraints, and the fitness function can be expressed as Equation (19):

$$F' = \sum_{i=1}^{N} (X_i + Y_i - YS_i)^2 \tag{19}$$

2.3.3. Modified method

Unlike the penalty function method and the limited search space method, the modified method is only to select X_i and Y_i as iteration variables. The feasible ranges of X_i and Y_i are [0, YS_i] and [0, $YS_i - X_i$], respectively. The other two variables, Z_i and PS_i, can be derived in the iteration processes according to the operation rule of the reservoir. The specific steps of the modified method are as follows:

(1) Set parameters including crossover rate and mutation rate;
(2) Randomly initialize the populations which consist of X_i and Y_i;
(3) Determine the Z_i and PS_i according to the operation rule of the reservoir: the temporary water storage of the reservoir can be calculated using Equation (20), without considering the water replenishment Z_i and water spill PS_i.

$$V_i = V_{i-1} + LS_i - EF_i - X_i \tag{20}$$

Then this method determines the values of water replenishment and spill using Equations (9)–(13), and modifies the water storage of the reservoir in each period, which is expressed as Equation (21):

$$V_i' = V_i + Z_i - PS_i \tag{21}$$

(4) Calculate the fitness function, which can be expressed as Equation (22):

$$F' = \sum_{i=1}^{N} (X_i + Y_i - YS_i)^2 + \sigma \sum_{j=2}^{3} ZP_j \tag{22}$$

In each iteration, this method checks the water storage of the reservoir at the end of each period, and determines the value of water replenishment and spill according to the operation rule. So there is no need to establish the constraint penalty functions for the constraint of the operation rule.

(5) Seek the optimal solution: If $F' \le F_{\min}$, then $F_{\min} = F'$.
(6) Enter the next generation after selection, crossover and mutation operations and repeat steps (3)–(5) until the termination condition is met.

The specific procedure is shown in Figure 2.

In the figure: V_0 is the initial water storage, G is the number of iterations, L is the size of the population, M is the number of genes, a is the crossover rate, and b is the mutation rate.

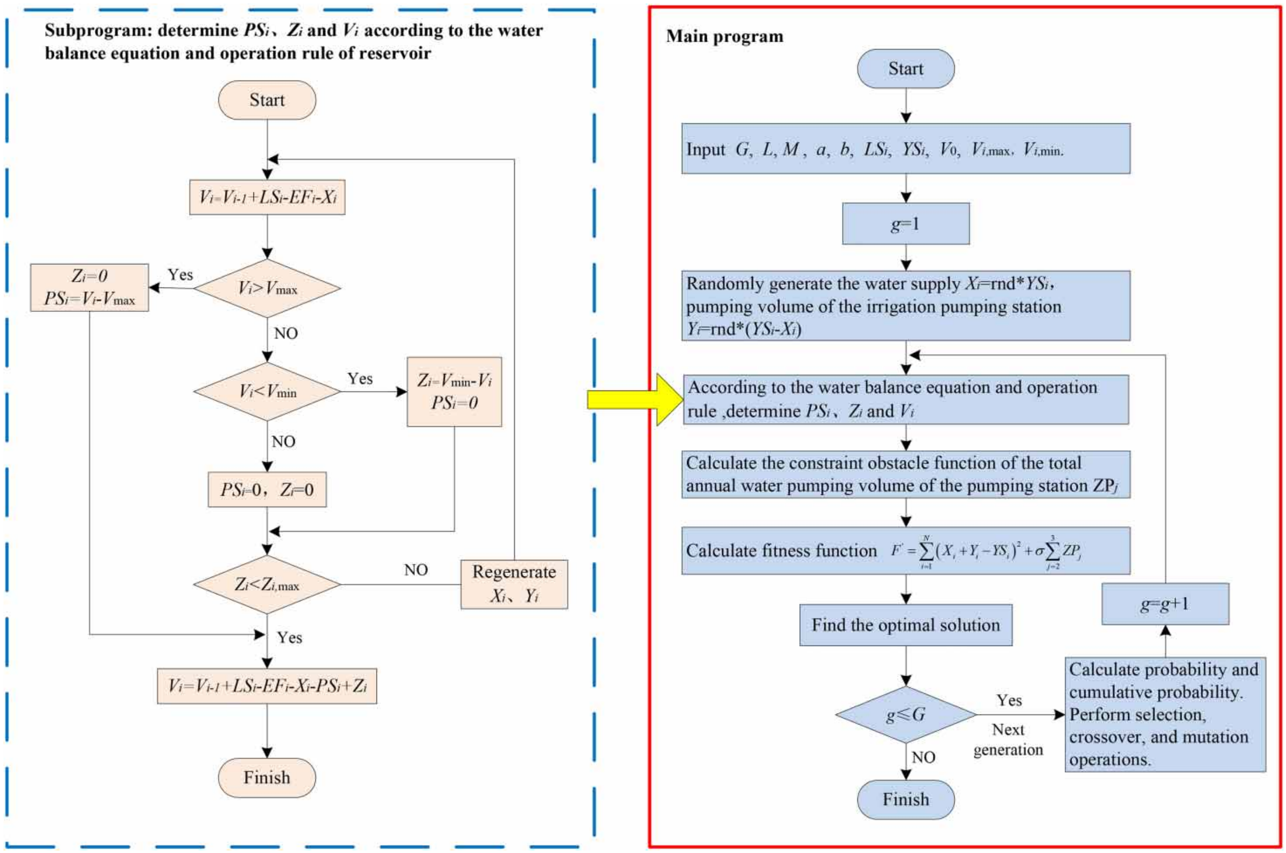

Figure 2 | Flow chart of the modified method.

3. CASE STUDY

The optimization model developed in this study was applied in the system of Pingshan reservoir, East-Pingshan pumping station and West-Pingshan pumping station, which is located in the Liuhe district of Nanjing, China, as shown in Figure 3.

The main function of the system is to supply irrigation water. In the system, the Pingshan reservoir and East-Pingshan station directly supply water for the irrigation area while the West-Pingshan station replenishes the Pingshan reservoir with water before the water level of the reservoir goes below the lower boundary limit. The main characteristics of Pingshan reservoir, West-Pingshan station and East-Pingshan station are shown in Tables 1 and 2.

The operation cycle of the system in this study is one year, which is divided into 20 periods: the flood season from June to September is also the peak period of irrigation for paddy fields, which is divided by ten days, and the rest of the year is divided into monthly periods. The data of inflow, evaporation and water demand of each period at the 50% (median water supply) and 75% (general drought year) probability of exceedance are shown in Tables 3 and 4, respectively. In addition, because the annual variation of evaporation is small, this paper uses annual average evaporation in the calculation.

Using the genetic algorithm, the three aforementioned methods for dealing with the constraints, including the penalty function method, the limited search space method and the modified method, were adopted to solve this nonlinear optimization model for the joint operation of a reservoir and two pumping stations. The value of the penalty factor (σ) was 50. The value of initial water storage (V_0) was 110 (10^4 m^3). And the values of GA parameters were as follow: the number of iterations (G) was 500, the size of the population (L) was 100, the number of genes (M) was 20, the crossover rate (a) was 0.6, and the mutation rate (b) was 0.05.

4. RESULTS AND DISCUSSION

As shown in Table 5, both the penalty function method and the modified method could obtain the final objective function value, but the limited search space method failed. This was because when the limited search space method was used to handle the

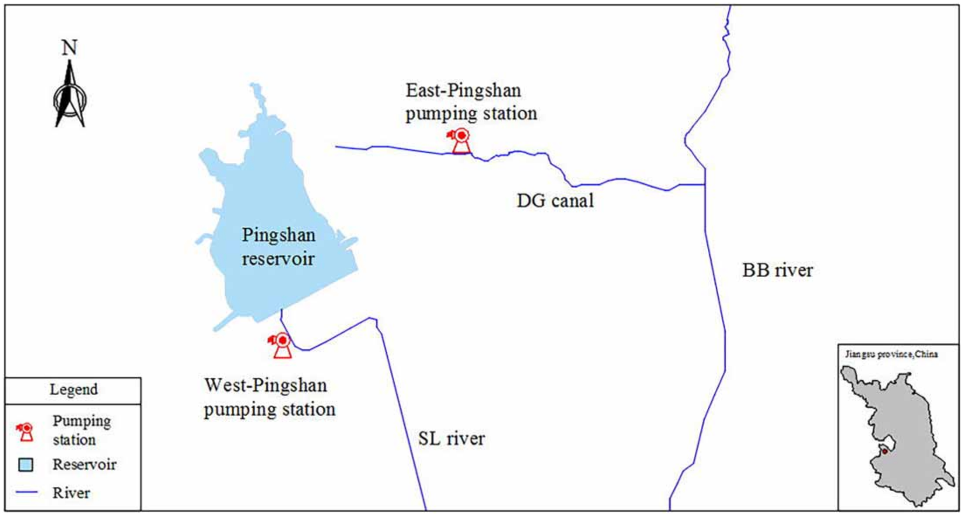

Figure 3 | Location and layout of the system.

Table 1 | Characteristics of Pingshan reservoir

Dead storage capacity (10^4 m^3)	Active capacity (10^4 m^3)	Catchment area (km^2)	Irrigation area (hm^2)
50	120	7.59	0.77

Table 2 | Characteristics of Pingshan stations

Name	Design flow (m^3/s)	Annual total pumping water volume (10^4 m^3)	Operating hours (h/d)
East-Pingshan station	0.48	200	22
West-Pingshan station	0.70	200	22

Table 3 | Water quantities of reservoir at the 50% probability of exceedance (10^4 m^3)

Period	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Early Jun.	Mid Jun.	
Inflow	14	30	11	2	10	13	10	23	8	36	
Evaporation	1	1	1	1	1	1	1	2	1	1	
Water demand	21	33	2	1	2	5	7	19	8	118	
Period	**Late Jun.**	**Early Jul.**	**Mid Jul.**	**Late Jul.**	**Early Aug.**	**Mid Aug.**	**Late Aug.**	**Early Sep.**	**Mid Sep.**	**Late Sep.**	**Total**
Inflow	7	22	16	17	21	12	14	5	11	4	286
Evaporation	2	2	2	2	2	2	2	2	2	2	31
Water demand	29	57	49	73	69	45	41	7	1	5	592

constraints, each population of the genetic algorithm required repeated crossover and mutation operations to produce a set of feasible solutions that met the constraints, instead of only performing crossover and mutation once per generation.

From Table 5, it is indicated that the modified method is significantly better than the penalty function method from the perspective of the final optimal results. At the 50% probability of exceedance, the total water shortage obtained with the

Table 4 | Water quantities of reservoir at the 75% probability of exceedance (10^4 m^3)

Period	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Early Jun.	Mid Jun.	
Inflow	9	26	8	0	8	11	8	20	2	32	
Evaporation	1	1	1	1	1	1	1	2	1	1	
Water demand	26	39	3	3	3	4	5	12	3	122	
Period	**Late Jun.**	**Early Jul.**	**Mid Jul.**	**Late Jul.**	**Early Aug.**	**Mid Aug.**	**Late Aug.**	**Early Sep.**	**Mid Sep.**	**Late Sep.**	**Total**
Inflow	0	19	9	15	13	11	11	2	11	0	215
Evaporation	2	2	2	2	2	2	2	2	2	2	31
Water demand	33	61	55	84	76	55	53	10	2	7	656

Table 5 | Final optimal results of different methods

Probability	Methods	Objective function value	Water shortage (10^4 m^3)	Water spill (10^4 m^3)
50%	Penalty function method	37	21	113
	Modified genetic algorithm	4	4	6
75%	Penalty function method	169	43	19
	Modified genetic algorithm	114	28	0

modified method is reduced by 80.9% and the total water spill is reduced by 94.7% compared against the penalty function method. At the 75% probability of exceedance, the total water shortage obtained with the modified method is reduced by 34.9% and the total water spill is reduced by 100% compared against the penalty function method. This is because the modified method makes full use of the storage capacity of the reservoir and reduces the pumping water of the pumping station, thereby reducing the water spill.

The inappropriate situation that the water replenishment and spill occurs at the same period, appeared in the operation processes obtained with the penalty function method as shown in Figures 4 and 5. However, this kind of water replenishment and spill is unacceptable in the actual reservoir management. The traditional genetic algorithms including the penalty function method and search space limitation method select X_i, Y_i, Z_i and PS_i as iteration variables. Before the iteration, all the iteration variables are generated, and then the water storage is calculated according to the water balance equation. Therefore, it is difficult to meet the constraints of if-statements like the operation rule of the reservoir, and the unreasonable situation that the water replenishment and spill will occur at the same time.

Different from traditional genetic algorithms, the modified genetic algorithm selects X_i and Y_i as iteration variables, reducing the model dimension from four dimensions to two dimensions. What is more, when dealing with the constraint of the operation rule of the reservoir, the modified genetic algorithm calculates the temporary water storage according to Equation (20) first, and then determines the volume of water replenishment and spill according to Equations (9)–(13), and finally revises water storage. Therefore, the modified genetic algorithm can avoid unreasonable water replenishment and spill. As a result, this method shows better adaptability to the operation rule as well as solving the problem with equality constraints and constraints of if-statements which traditional genetic algorithms cannot solve.

5. CONCLUSION

This paper proposes a nonlinear optimization model for the joint operation of a system of a reservoir and two pumping stations. One such system in Nanjing, China, was selected for a case study. It compares the impact on results between the traditional genetic algorithm which uses the penalty function and limited search space method to deal with the constraints and the modified genetic algorithm which uses the water supply and the water volume of the irrigation pumping station as the

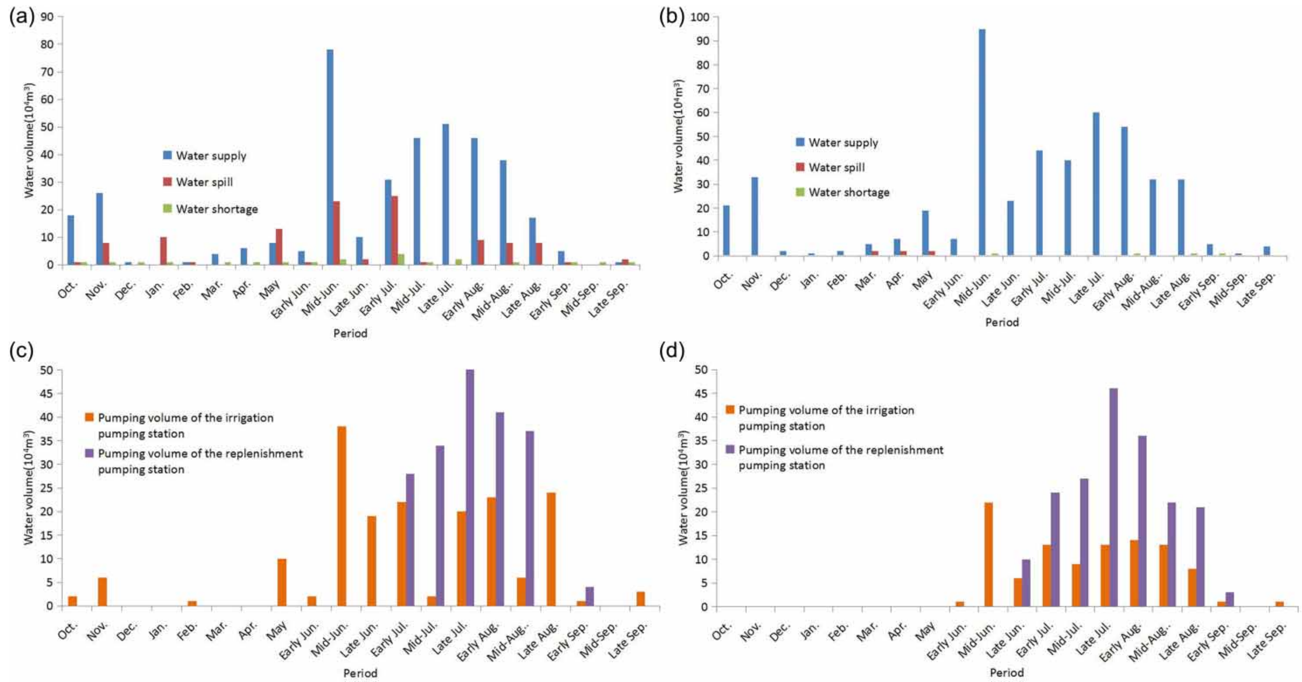

Figure 4 | Optimized configuration results at the 50% probability of exceedance: (a) reservoir operation process (penalty function method); (b) reservoir operation process (modified genetic algorithm); (c) pumping volume of the irrigation pumping station and the replenishment pumping station (penalty function method); (d) pumping volume of the irrigation pumping station and the replenishment pumping station (modified genetic algorithm).

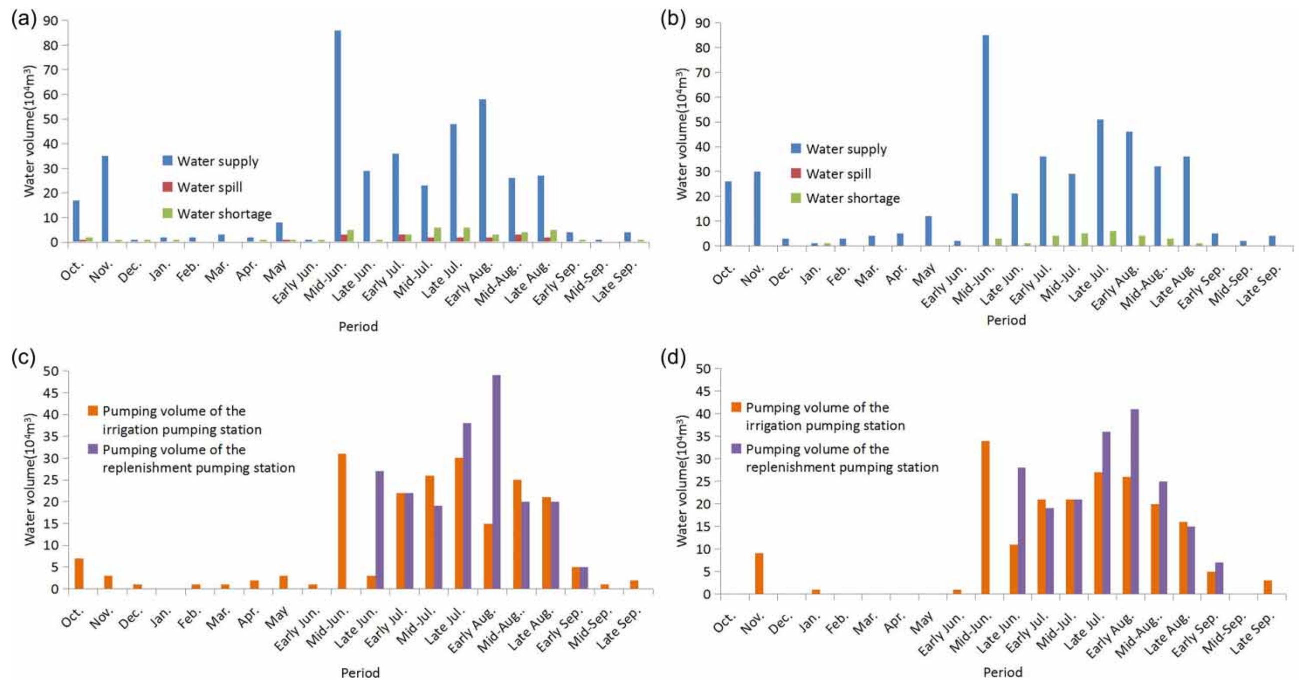

Figure 5 | Optimized configuration results at the 75% probability of exceedance: (a) reservoir operation process (penalty function method); (b) reservoir operation process (modified genetic algorithm); (c) pumping volume of the irrigation pumping station and the replenishment pumping station (penalty function method); (d) pumping volume of the irrigation pumping station and the replenishment pumping station (modified genetic algorithm).

iteration variables. The results show that the modified genetic algorithm reduces water spill and water shortage, and solves the constraints of if-statements like the operation rule of the reservoir.

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DATA AVAILABILITY STATEMENT

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

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