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Reservoir Operation Sequence- and Equity Principle-Based Multi-Objective Ecological Operation of Reservoir Group: A Case Study in a Basin of Northeast China

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Abstract: The sequence of reservoir operations has a profound influence on the regulation and storage capacity of reservoir groups to effectively utilise the natural water inflow and external water transfer in the basin, especially for reservoir groups with water supply tasks. This study establishes the reservoir operation sequence (ROS) of four reservoir group modes, aiming at national economic and ecological water consumption, constructs a model of ROS-based multi-objective ecological operation of the reservoir group, and uses the particle swarm optimisation (PSO) method to optimise the solution. Analysing the results of the three schemes in two scenarios at the Yinma River Basin (YRB) indicates that after the Central Jilin Water Supply Project is put into operation, not only will the production and living water be effectively improved, but also the ecological water in the basin. Then, we compared the optimisation results of different water supply sequences in series and parallel reservoirs, which illustrates that the ROS of the four modes formulated in this research is the optimal water supply sequence.

Keywords: reservoir operation sequence; ecological operation; multi-objective; reservoir group

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1. Introduction

The reasonable allocation of water resources in a watershed is necessary because of the spatiotemporal asynchronism of natural inflows and water demand [1]. In previous decades, the unchecked development of human society has led to a continuous increase in the demand for water [2]. Many residential areas are at high risk of water shortage due to the frantic exploitation and utilization of water resources [3], especially in arid areas such as northern China [4–7], southwestern USA [8], and the Middle East [9]. In order to ease the water contradiction and reduce the risk of water shortage, previous studies have put forward many research methods for the optimal allocation of water resources in watersheds [1,10–12]. As a control project of water resources optimization, the reservoir with regulating and storage function has an essential influence on meeting the specific demand of water resources in the basin and is the key research object for the optimal allocation of water resources [13].

The influence of the reservoir project on human society is a double-edged sword [14,15]. On the one hand, people benefit from the functions of reservoirs, such as water supply, flood control, irrigation, power generation, and shipping [16]. On the other hand, as the reservoir greatly changes the spatiotemporal distribution of natural inflows, human beings have to face the negative impact of the reservoir on the watershed ecosystem [17]. Hence, it is imperative to carry out the reasonable ecological operation of water resources to meet the needs of human social development and the ecological environment [18,19].

Since the continuity of water demand is not synchronized with the seasonal characteristics of natural runoff [20], it is necessary to build suitable reservoirs to optimize the water resources in the basin [21]. Because of the different storage capacity of each reservoir, the distribution of the reservoir in the basin has a very important influence on the optimisation results for the entire reservoir system [1,22]. Due to the directivity of water flow, the difference in reservoir storage capacity, and the geographical location of the water demand area relative to the reservoir, the sequence of the reservoir operation has a profound influence on the results of optimal water resource allocation in the basin, especially for reservoir groups with water supply tasks [23,24]. Furthermore, for a reservoir that supplies water to many water units, how to distribute water among different units to reflect the fairness of social development is also a realistic problem faced by water resource managers when the water supply for a certain period of time cannot meet the water demand [25].

Scholars have developed many optimisation algorithms for optimal water resources, including reservoir operations [26], such as linear programming (LP) [21], nonlinear programming (NLP) [27], and dynamic programming (DP) [28] in earlier years, as well as progressive optimality algorithms [29], artificial neural networks (ANNs) [25], fuzzy methods [30], genetic algorithms (GAs) [31], ant colony optimisation (ACO) [32], and particle swarm optimisation (PSO) [23,24] more recently. In particular, PSO, which has the advantages of excellent principle, simple performance, and fast convergence speed [33], has been favoured by researchers and is widely used in research fields on a reservoir's optimal operation [1,22]. However, these optimisation simulations tend to focus on a single reservoir or a simple system [1,23], and there are few studies on the optimal operation of reservoir groups considering an entire basin. Meanwhile, the previous optimisation processes focused on decision variables, such as reservoir discharge or water supply [22,24], and few studies have addressed the effect of the reservoir operation sequence (ROS) on the optimisation results.

The present study takes a basin of northeast China as an example, constructs a model of the reservoir operation sequence- and equity principle-based multi-objective ecological operation of the reservoir group on the basis of a generalized water resource allocation network diagram of the basin, and uses the PSO method to optimise the solution. Then, it carries out the demonstration exercise of ecological operation according to the analysis of the current annual water consumption and the forecast of the future annual water demand. The aim is to enrich the research on optimal reservoir operation and provide technical support for the water resource management department to optimize water resource scheduling.

2. Material and Methods

2.1. Multi-Objective Ecological Operation Model

2.1.1. Objective Function

The multi-objective ecological scheduling of the present study aims to seek maximum comprehensive benefits to society and ecology. The social objective is the sum of the water supply assurance rate (WSGR) of each water consumption unit. The ecological objective is the sum of ecological flow suitability (EFS) of each river section.

1. Maximize WSGR

The objective function of the maximized WSGR is expressed as Equation (1):

$$max(WSGR) = max\sum_{i=1}^{N}\sum_{t=1}^{T}\frac{S_{i,t}}{W_{i,t}} \tag{1}$$

where N and T represent the number of generalised calculation units in the model and total scheduling stages, respectively. $S_{i,t}$ (m^3) and $W_{i,t}$ (m^3) represent the water supply and demand of the i-th calculation unit in the t-th stage, respectively.

2. Maximize EFS

The objective function of the maximized EFS is expressed as Equation (2):

$$max(EFS) = max\sum_{j=1}^{M}\sum_{t=1}^{T}\frac{Q_{j,t}}{Q_{j,t}^{E}} \quad (2)$$

where M represents the number of monitoring sections for the ecological flow. $Q_{j,t}$ (m^3/s) and $Q_{j,t}^E$ (m^3/s) represent the actual flow and ecological flow of the j-th monitoring section in the t-th stage.

2.1.2. Constraints

1. Water balance constraint:

$$V_{k,t+1} = V_{k,t} + \left(I_{k,t} + I_{k,t}^{D} - O_{k,t} - O_{k,t}^{D} - RS_{k,t}\right)\cdot\Delta t - RE_{k,t} - RF_{k,t} \quad (3)$$

where $V_{k,t+1}$ (m^3) and $V_{k,t}$ (m^3) signify the storage capacity of the k-th reservoir in the t and (t + 1)-th stages, respectively. $I_{k,t}$ (m^3/s), $I_{k,t}^D$ (m^3/s), $O_{k,t}$ (m^3/s), $O_{k,t}^D$ (m^3/s), and $RS_{k,t}$ (m^3/s) are the inflow, diversion inflow, outflow, diversion outflow, and supply flow of the k-th reservoir in the t-th stage, respectively; and Δt (s) is the scheduling stage; $RE_{k,t}$ (m^3) and $RF_{k,t}$ (m^3) signify the evaporation and seepage of the k-th reservoir in the t-th stage, respectively.

2. Reservoir outflow and water supply constraints:

$$(1-\alpha)\cdot W_t \le RS_{k,t}\cdot\Delta t \le W_t \quad (4)$$

$$Q_{k,t}^{E} \le O_{k,t} \le Q_{max} \quad (5)$$

where W_t (m^3) represents the water demand for the reservoir supply channel. α (dimensionless) is the failure depth factor, which represents the ratio of water shortage to water demand (in a dry year, when water supply cannot meet water demand, the water supply can be appropriately reduced, but it should not be lower than the water shortage depth allowed by each user. In this study, α of domestic, industrial, and agricultural water is 0.05, 0.10, and 0.30, respectively). $Q_{k,t}^E$ (m^3/s) and Q_{max} (m^3/s) signify the ecological flow in the t-th stage and overflow capacity of the corresponding river section, respectively.

3. Reservoir storage capacity constraint:

$$V_k^d \le V_{k,t} \le V_{k,t}^{max} \quad (6)$$

where V_k^d (m^3) signifies the dead capacity of the k-th reservoir and $V_{k,t}^{max}$ (m^3) signifies the maximum permissible storage capacity of the k-th reservoir in the t-th stage.

4. Channel overflow capacity constraints:

$$O_{k,t} \le Q_{kmax} \quad (7)$$

$$O_{k,t}^{D} \le Q_{kmax}^{D} \quad (8)$$

$$RS_{k,t} \le RS_{kmax} \quad (9)$$

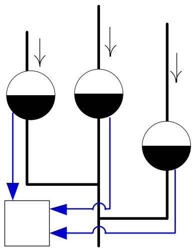
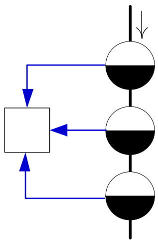
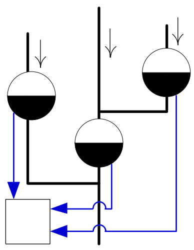
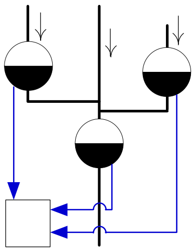
where Q_{kmax} (m^3/s), Q_{kmax}^D (m^3/s), and RS_{kmax} (m^3/s) signify the flow capacity of the water supply, diversion inflow, and diversion outflow channel, respectively.

2.1.3. Reservoir Operation Sequence (ROS) and Equity Principle (EP)

1. Reservoir Operation Sequence (ROS)

Because of the diversity of the reservoir group combination mode, the operation mode of the reservoir group is also complex and changes in actual operation. Several primary combination modes with operation rules are introduced in this study (Table 1).

Table 1. The primary combination modes and operation rules of the reservoir group.

Mode	Schematic Diagram *	Reservoir Operation Sequence
A		The water supply sequence is based on the utilisable reservoir storage capacity, from small to large.
B		The water supply sequence depends on the reservoir locations, which proceed successively from the downstream reservoir to the upstream reservoir.
C		The two tandem reservoirs on the right are equivalent to a reservoir, and the utilisable capacity of the equivalent reservoir is equal to the sum of the reservoir's utilisable capacity in the series system. Thus, the equivalent reservoir forms a parallel system with the remaining reservoirs, and the water supply sequence is determined according to the operation rules of Mode A. Additionally, the water supply sequence of the series reservoirs follows Mode B.
D		The two upstream parallel reservoirs are equivalent to a reservoir. Thus, the equivalent reservoir forms a series system with the remaining reservoirs, and the water supply sequence of the reservoirs is determined according to the operation rules of Mode B. Additionally, the water supply sequence of the parallel reservoirs follows Mode A.

* Legend in schematic diagram: 

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2.2. Equity Principle (EP)

The EP is explained as follows: suppose a water supply project supplies n units of water supply, the project water supply is (m^3) in the t-th stage, and the water demand of each unit is $D_{i,t}$ (m^3) (Figure 1). If $\sum_{i=1}^{n} D_{i,t} > S_t$, the amount of water actually obtained by each water unit from the water supply project, assumed as $A_{i,t}$, is allocated according to Equation (10).

$$A_{i,t} = \frac{S_t}{\sum_{i=1}^{n} D_{i,t}} \cdot D_{i,t} \quad (10)$$

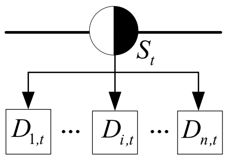

Figure 1. Schematic of EP.

2.2.1. Optimisation Algorithm

The present study adopted a PSO to optimise the solution. PSO is a population-based optimisation technique that originated from a study on the foraging behaviour of flocks of birds [33]. The PSO algorithm adopts a velocity-position search model to make each particle of a population follow the current superior particle at a certain speed and search for the optimal solution in the solution region [22]. We let x and v represent the particle spatial position and the searching speed of m particles swarm $X = (x_1, x_2, \cdots, x_m)^T$ in *D-dimensional* (D = 30 in this study) space, respectively. $x_i = (x_{i1}, x_{i2}, \cdots, x_{iD})$ and $v_i = (v_{i1}, v_{i2}, \cdots, v_{iD})$ indicate the position of the i-th particle of the population and the particle's searching velocity, respectively. $P_i = (P_{i1}, P_{i2}, \cdots, P_{iD})$ and $P_G = (x_{G1}, x_{G2}, \cdots, x_{GD})$ denote the best position of the i-th particle and the global best position of the m particle swarm, respectively. The iterative updates of the particle velocity and position follow Equations (11) and (12).

$$v_i^{(n+1)} = \omega^{(n)} v_i^{(n)} + c_1 r_1^{(n)} \left(P_i^{(n)} - x_i^{(n)} \right) + c_2 r_2^{(n)} \left(P_G^{(n)} - x_i^{(n)} \right) \quad (11)$$

$$x_i^{(n+1)} = x_i^{(n)} + v_i^{(n+1)} \quad (12)$$

where $\omega^{(n)}$ is the inertia weight of the i-th particle, and the weight's value varies from 0.9–0.4 [34]; c_1 and c_2 are positive constant parameters, called learning factors; and $r_1^{(n)}$ and $r_2^{(n)}$ are random numbers in the interval [0, 1]. When $\omega^{(n)}$ = 0.729 and $c_1 = c_2 = 2.05$, the convergence of the algorithm is favorable [35].

This study combines ROS and PSO to form the ROS–PSO method (Figure 2, Supplementary Material Text S1) for the optimisation solution.

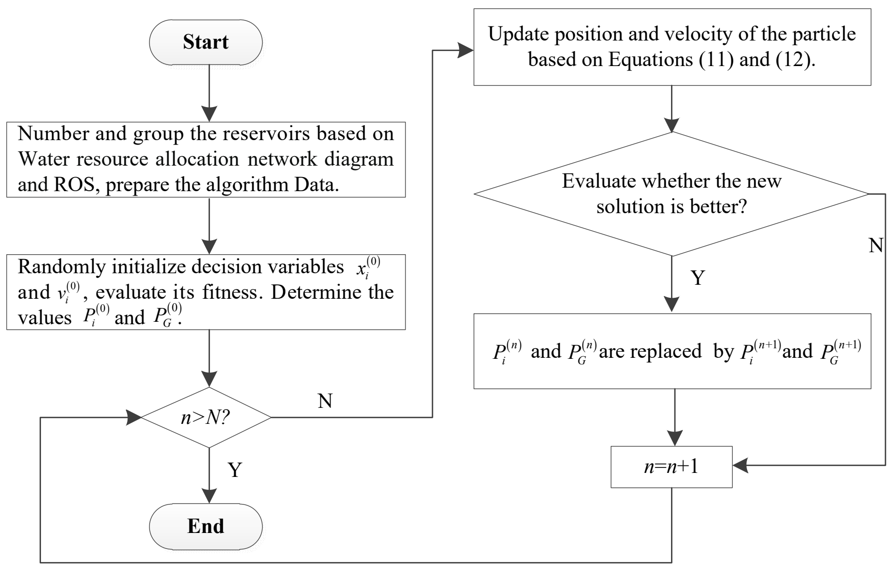

Figure 2. Flowchart of solving optimal operation model through the ROS–PSO method.

2.2.2. Data Input

The present study develops a watershed reservoir ecological operation model (WREOP) in the C language program. The input data of WREOP contain the national economic water demand, historical reservoir inflows, reservoir parameters, river parameters, channel parameters, and control section ecological flow. These data are described in detail in the section of "Case Study."

2.3. Case Study

2.3.1. Study Area and Data

The present research takes the Yinma river, a basin in northeast China (Figure 2), as a case study. The Yinma River Basin (YRB) covers an area of 17.4 thousand square kilometers, and the length of the mainstream is 387 km. The YRB belongs to the continental monsoon climate zone of the northern temperate zone. The region's water vapor mainly comes from the Pacific Ocean. In the YRB, the flood season is from April to September, and the rest of the time is the non-flood season. There are seventeen reservoirs (Figure 3, Table S1) and two external water diversion projects in the basin (Figure 3). One is the Central Jilin Water Supply Project (CJWSP) with a designed water supply capacity of 8.66 × 10^8 m^3/year; the other is the Songhua River–Changchun Diversion Project (SCDP) with a designed water supply capacity of 2.67 × 10^8 m^3/year. The YRB is a relatively water-deficient watershed, and the shortage of water resources is the main factor that restricts the social development in this region. Besides, the irrational use of water resources makes the watershed face severe ecological problems. Hence, an efficient and reasonable way of utilising water resources is particularly important.

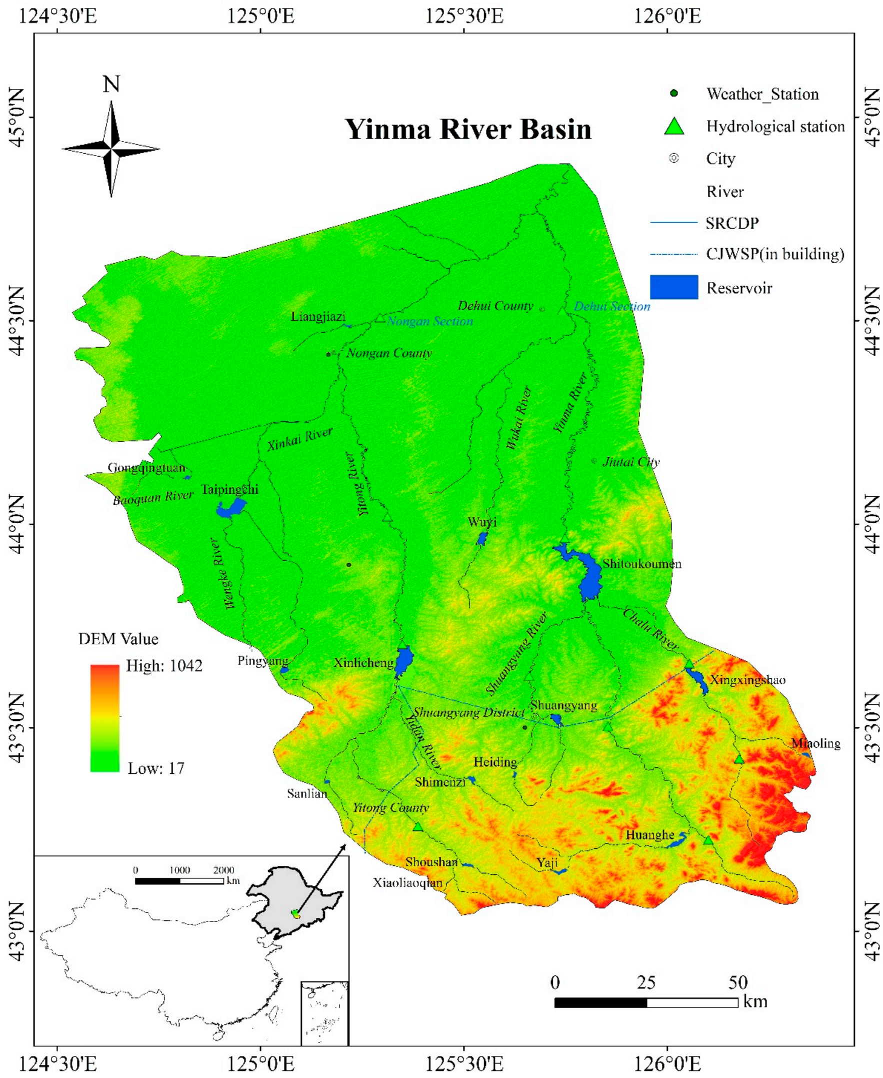

Figure 3. Geographical location, DEM, weather station, river, and hydraulic engineering distribution of the study area.

In this study, the data on national economic water demand are from the Study on Optimal Allocation and Carrying Capacity of Water Resources in Changchun–Jilin Combined Metropolitan Areas (http://tjj.jl.gov.cn/, accessed on 10 January 2022). The reservoir historical inflow data during 1956–2016 were calculated using meteorological data and river flow data collected from the Jilin Hydrology Bureau. The reservoir parameters, river parameters, and channel parameters were collected from the Jilin Provincial Water Resources Department (http://slt.jl.gov.cn/, accessed on 12 January 2022). According to the precision of WREOP, the long-term monthly data were adopted to optimise the simulation.

2.3.2. Calculation of Ecological Flow

The purpose of maintaining the river's basic ecological flow (BEF) is to prevent rivers from shrinking and cutting off the flow, as well as to maintain the basic stability of the river ecosystem [36]. However, the BEF determination is closely related to the life characteristics of aquatic life, the growth of aquatic organisms, and the restriction of water quantity [37]. Hence, the BEF is not a fixed value. In order to aim at the characteristics of the YRB during the dry season, the 7Q10 method [38] was adopted to calculate the BEF. In the flood season, 10% of the average annual runoff of the river section was selected as the BEF [36]. The Tennant method [39] was adopted for ecological suitable flow (ESF); the ESF in the flood season and non-flood season is 30% and 10% of the annual average monthly runoff respectively. If the ESF is smaller than the ecological base flow, the ecological base flow is taken as the ESF.

2.3.3. Scheduling Network Generalisation

According to the river distribution and flow direction of the YRB, as well as the identification of the water intake, water consumption, and drainage system outside of the river, an appropriate generalisation is made (Figure S1 and Table S2).

2.3.4. Scheduling Schemes Setting

In the present study, three scheduling schemes under two scenarios were proposed. The specific scenarios and schemes are described in Table 2:

Table 2. Scheduling schemes' setting in the present study.

Year	Scenario Description	Ecological Scheduling Scheme	No.
2015	Before the water supply of Central Jilin Water Supply Project	Reservoir group operation not considering ecological flow	P1
		Reservoir group operation considering ecological base flow	P2
		Reservoir group operation considering ecological suitable flow	P3
2030	After the water supply of Central Jilin Water Supply Project	Reservoir group operation not considering ecological flow	P1
		Reservoir group operation considering ecological base flow	P2
		Reservoir group operation considering ecological suitable flow	P3

3. Results

3.1. Water Demand Prediction

According to the prediction of water demand (Table S3), the total water demand of YRB is 1.81×10^8 m^3 in 2015 and 2.71×10^8 m^3 in 2030, respectively. Water units are divided into three categories: urban, irrigation area, and river internal (Figure 4). The water demand of urban/irrigation area/internal river was 5.89/3.85/8.36 $\times 10^8$ m^3 in 2015, and the water demand of urban/irrigation area/internal river is 11.86/3.58/3.57 $\times 10^8$ m^3 in 2030. The EBF of the Dehui section in flood/non-flood season is 2.63/1.87 m^3/s, and the EBF of the Dehui section in flood/non-flood season is 1.27/1.14 m^3/s (Figure 5a). The ESF reached its maximum in August, with 38.29 m^3/s in the Dehui section and 15.37 m^3/s in the Nongan section (Figure 5b).

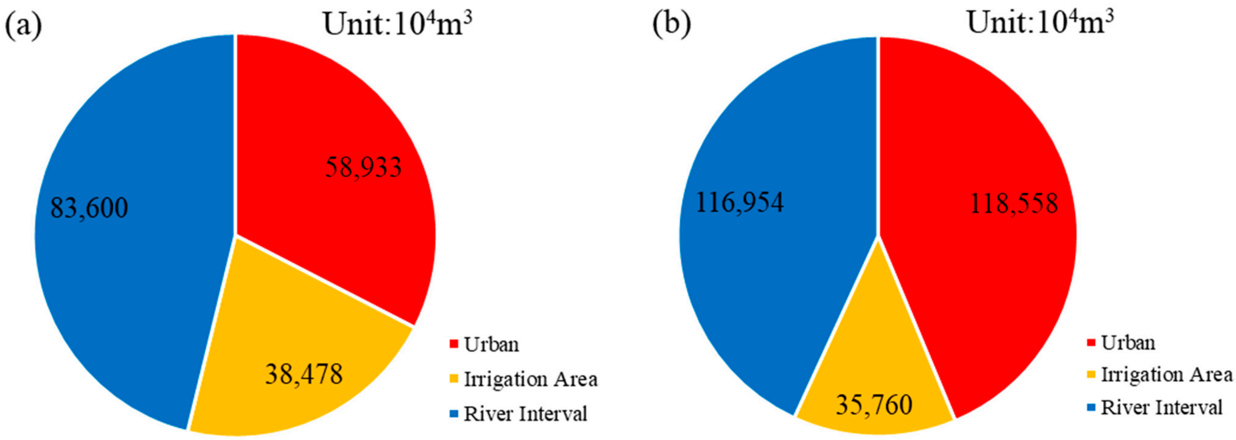

Figure 4. Water demand prediction of each category in YRB: (**a**) in 2015 and (**b**) in 2030.

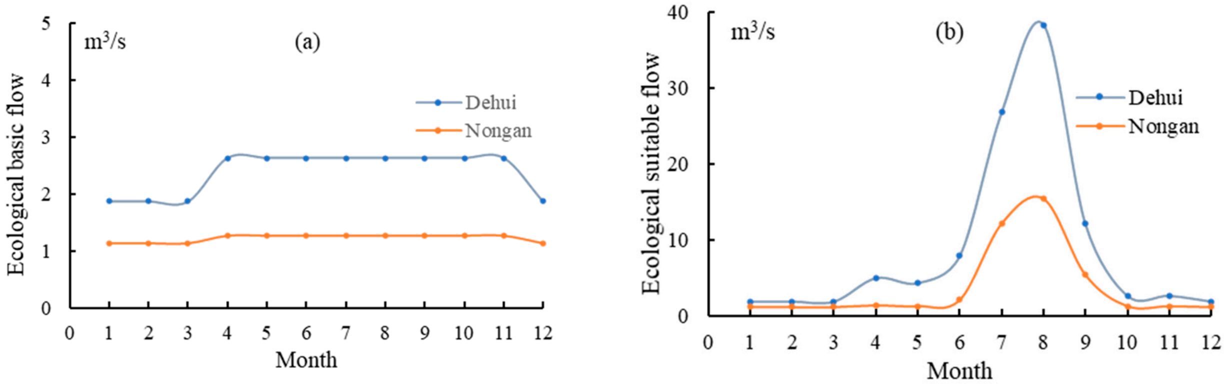

Figure 5. Control section of the ecological flow in YRB: (**a**) EBF and (**b**) ESF.

3.2. Supply-Demand Balance Analysis

In dry year, the water shortage of P1/P2/P3 was 7204/7819/9122 $\times$ 10^4 m^3 in 2015, and the water shortage rate of them was 3.98%/4.32%/5.04% (Figure 6a). The water shortage of P1/P2/P3 is 2170/5290/8708 $\times$ 10^4 m^3 in 2030, and the water shortage rate of them is 0.8%/1.95%/3.21% (Figure 6b). In a normal year, the water shortage of P1/P2/P3 is 5448/7204/8272 $\times$ 10^4 m^3 in 2015, and the water shortage rate of them is 3.01%/3.98%/4.57% (Figure 6a). The water shortage of P1/P2/P3 is 2062/2930/6348 $\times$ 10^4 m^3 in 2030, and the water shortage rate of them is 0.76%/1.08%/2.34% (Figure 6b). In a wet year, the water shortage of P1/P2/P3 was 3150/4634/5810 $\times$ 10^4 m^3 in 2015, and the water shortage rate of them was 1.74%/2.56%/3.21% (Figure 6a). The water shortage of P1/P2/P3 is 1519/2686/4747 $\times$ 10^4 m^3 in 2030, and the water shortage rate of them is 0.56%/0.99%/1.75% (Figure 6b).

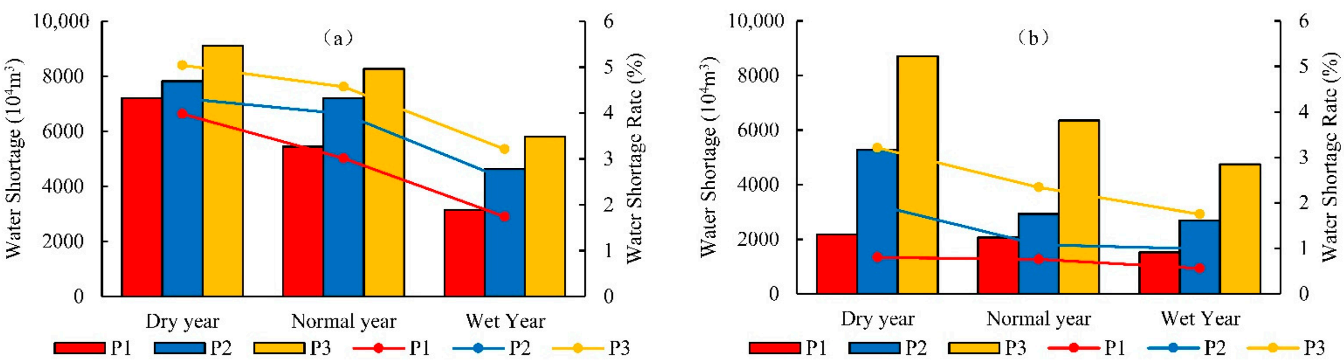

Figure 6. Water shortage and water shortage rate in YRB: (**a**) in 2015 and (**b**) in 2030.

Figure 7 shows the water shortage rate of each water consumption unit in urban, river internal, and irrigation areas. In 2015, the water shortage rate of urban/river internal/irrigation area water units in the dry year reached the maximum of 5.00%/7.99%/9.88%; in the normal year, it reached the maximum of 4.75%/6.42%/7.17%; and in the wet year, it reached the maximum of 0.90%/2.07%/3.11% in P3 (Figure 7c). In P1 and P2, some water units also have higher water scarcity rates (Figure 7a,b). In 2030, the water shortage rate of urban/river internal/irrigation area water units in the dry year reaches the maximum of 5.00%/7.99%/9.88%; in the normal year, it reaches the maximum of 2.09%/3.65%/4.23%; and in the wet year, it reaches the maximum of 3.11%/4.15%/5.12% in the P3 (Figure 7a,b). Compared with 2015, the water shortage rate of each water unit in 2030 has decreased, especially in urban water consumption units. Whether in 2015 or 2030, the water shortage rate of each water consumption unit shows an upward trend from P1 to P3.

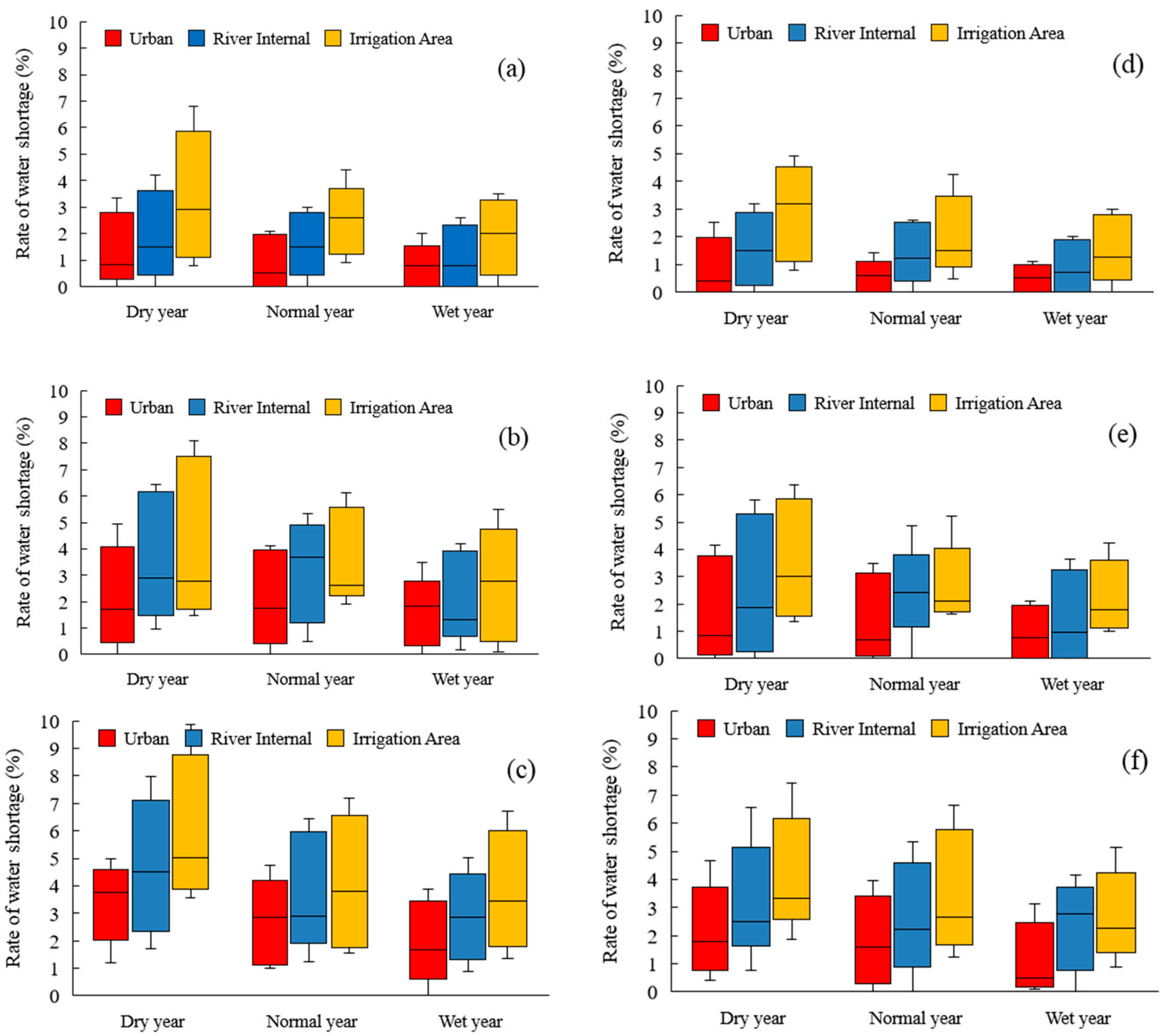

Figure 7. Box plot of water shortage rate of different schemes in each level year: (**a**) P1 in 2015, (**b**) P2 in 2015, (**c**) P3 in 2015, (**d**) P1 in 2030, (**e**) P2 in 2030, and (**f**) P3 in 2030.

3.3. Runoff of River Section

Figures 8 and 9, respectively, show the runoff of the Nongan and Dehui sections of different schemes in 2015 and 2030. The two sections' runoffs of the three schemes in 2015 and 2030 reach or exceed the EBF. In 2015, there were certain gaps between the runoff of the ESF from July to September in P1 and P2 in the dry and normal years (Figures 8a,b and 9a,b). Although the gaps narrowed in 2030 (Figures 8d,e and 9d,e), the ESF was still difficult to achieve. These gaps are closely related to the high agricultural water consumption during this period, especially in August. In 2015, The runoffs of P3 significantly increased compared with P1 and P2, but it still failed to reach the ESF in the dry and normal years (Figures 8a–c and 9a–c). In 2030, the runoffs of P3 exceed or are close to the ESF (Figures 8d–f and 9d–f). In the wet year, the runoffs of all schemes could reach the ESF except for a few months (Figures 8f and 9f).

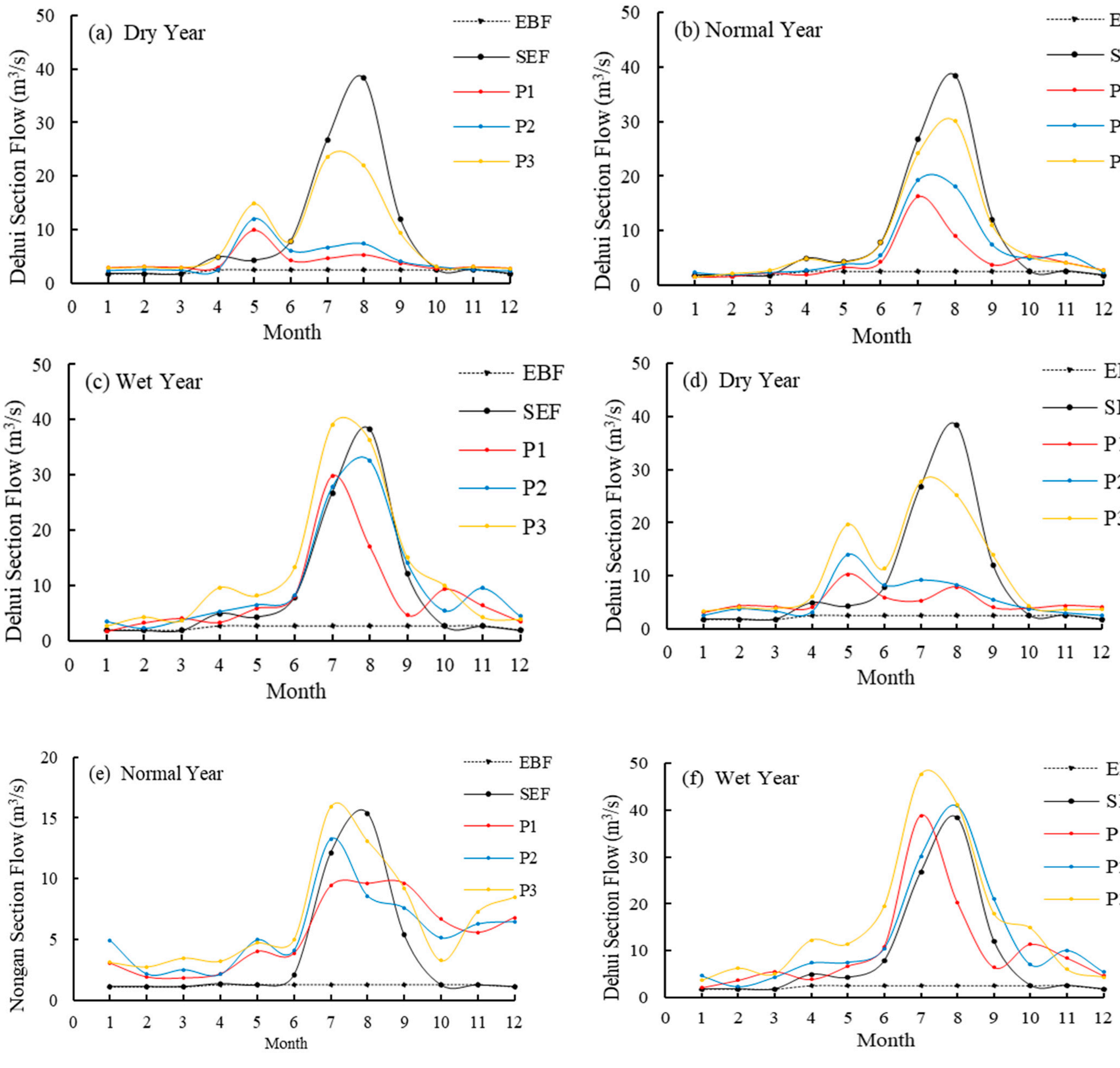

Figure 8. Plot of the Dehui section runoff of different schemes in each level year: (**a**–**c**) in 2015 and (**d**–**f**) in 2030.

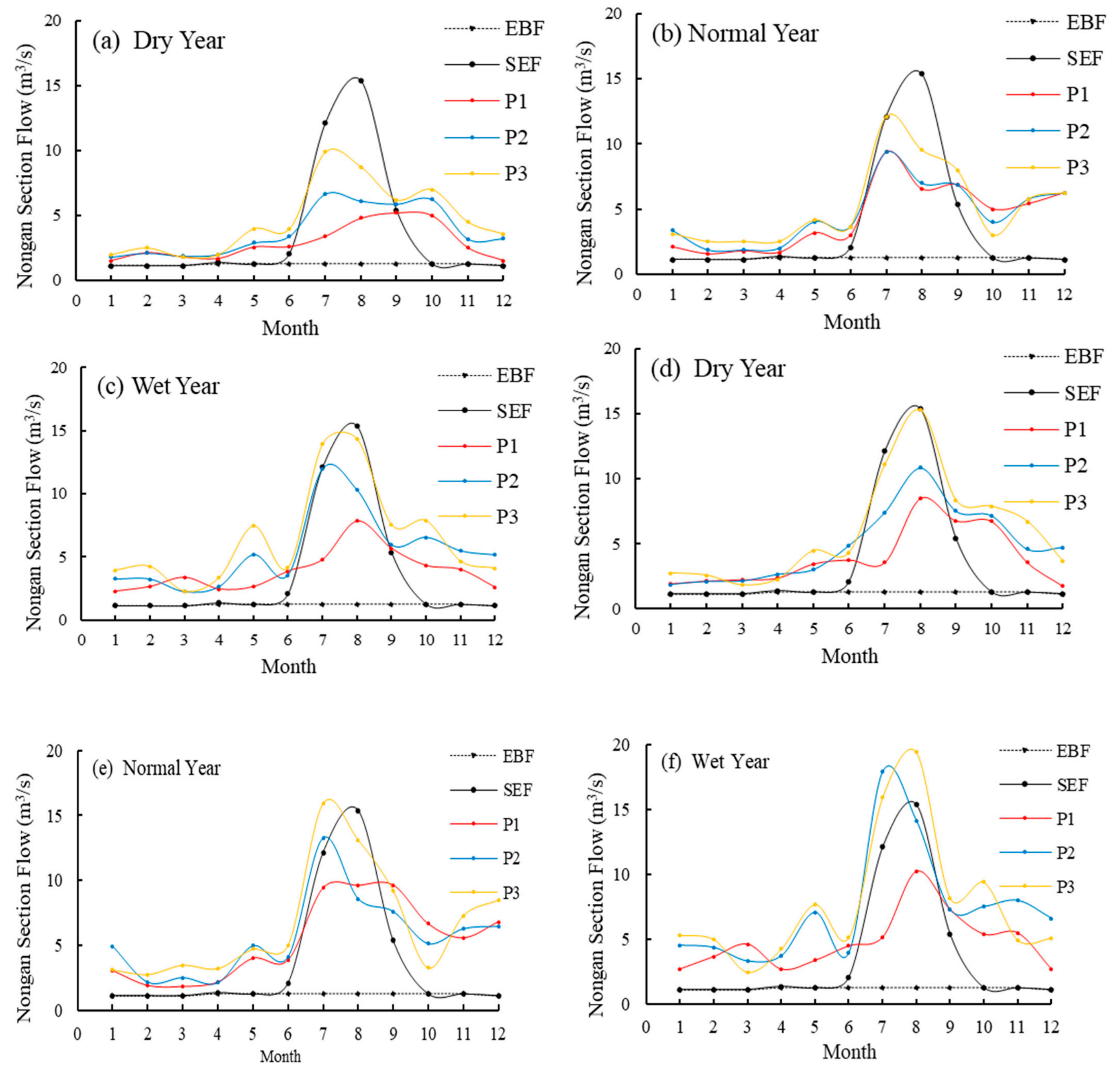

Figure 9. Plot of the Nongan section runoff of different schemes in each level year: (**a**–**c**) in 2015 and (**d**–**f**) in 2030.

4. Discussion

From previous reservoir operation practices in China, because most of the reservoir is facing a huge pressure to flood control and constant power demand, the current reservoir operation is mainly based on flood control and power generation [31,40]. The requirements of aquaculture, tourism, and improving water quality are sometimes appropriately balanced, but there is a lack of long-term effective routine operation schemes for these needs [36]. Meanwhile, the implementation of an ecological operation is mainly through administrative means and lacks legal provisions on ecological dispatching, which seriously restricts the sustainability of the ecological development of the watershed [30,41].

Because the quantization of dispatching the technical index of an ecological protection object lacks a unified standard, the technology of an ecological operation is not perfect [42]. Under the background of a water resource shortage, it is unrealistic to give consideration to all components in the ecosystem [43]. It is necessary first to determine the protected objects and their living environment, and then the relationship between hydrological characteristics (discharge, etc.) and the living environment can be quantitatively described. Finally, the appropriate water transfer time and the optimal water volume can be selected [32,44,45].

The ecological benefit evaluation is also an important part of reservoir ecological operation research [46]. The purpose of reservoir ecological operation is to supplement the lack of water in the ecological environment, which will inevitably reduce social and economical water consumption. How to balance the relationship between them and achieve the optimal comprehensive benefits of reservoir operation must reflect the ecological benefits of the reservoir [27,29]. Therefore, it is the key factor in realizing the reservoir ecological operation to establish the corresponding value evaluation system and evaluate the value of the reservoir ecological water transfer quantitatively [46].

In the current water supply system, one-to-one supply mode (one source supplies one water unit) is rare, and one-to-several (one source supplies several water units), several-to-one (several sources supply one water unit), or several-to-several (several sources supply several water units) supply mode, is normal. Therefore, the study of the operation rules of the reservoir groups is the core of reservoir ecological operation [27]. In this study, the EP rule ensures that water scarcity rates are consistent across regions in the event of water scarcity, reflecting that all regions enjoy equitable access to water resources. The reasonable ROS can improve the utilization efficiency of water resources in the basin to some extent.

For the multiple water sources supply system, because of the location of water sources in the basin and their different regulation and storage capacities, a reasonable supply sequence arrangement will positively impact the optimisation results. In order to compare the influence of different water supply sequences of series and parallel reservoir systems on the results, this study also optimised and simulated the supply and demand balance results of the other five water supply sequences for Mode C (Table 1). Figure 10 shows the annual water shortage rate of Unit 25 (Figure S1 and Table S2) with different water supply sequence optimisations in Mode C. It is obvious that Unit 25 has fewer years of water shortage in S1 (blue in Figure 10) than in other sequences, and the water shortage rate in the year of water shortage is also less than that in other sequences. The average annual water shortage rates of Unit 25 in the S1 water supply sequence were smaller than the results of other sequences. This demonstrates that S1 (ROS of Mode C in Table 1) is the optimal water supply sequence in the series and parallel reservoir group water supply system.

For the parallel reservoir system, owing to the limited regulation and storage capacity of reservoirs with small storage capacity, prioritizing the arrangement of water supply to the reservoirs with small storage capacity can reduce the amount of abandoned water in the reservoirs and effectively regulate and store the capacity of the parallel reservoir system. For the tandem reservoir system, it is impossible for the downstream reservoir discharge to flow into the upstream reservoir without external force spontaneously, and prioritizing the downstream reservoir water supply can avoid the ineffective abandoned water phenomenon in which the discharge from the upstream reservoir cannot be fully utilised. According to the above analysis, the water supply sequence S1 makes full use of the regulation and storage capacity of the series and parallel reservoir group system, thus making efficient use of upstream water. In contrast, S4 is the most unfavourable water supply sequence in this system, with more years of water shortage and a greater annual average water shortage rate than the other sequences.

Furthermore, Mode C is a combination of modes A and B, and Mode C's ROS actually follows the ROS of modes A and B. In the same way, Mode D combines modes A and B, and Mode D's ROS also follows the ROS of modes A and B. Hence, the results also reveal that the ROS of modes A, B, and D formulated in this research are optimal water supply sequences.

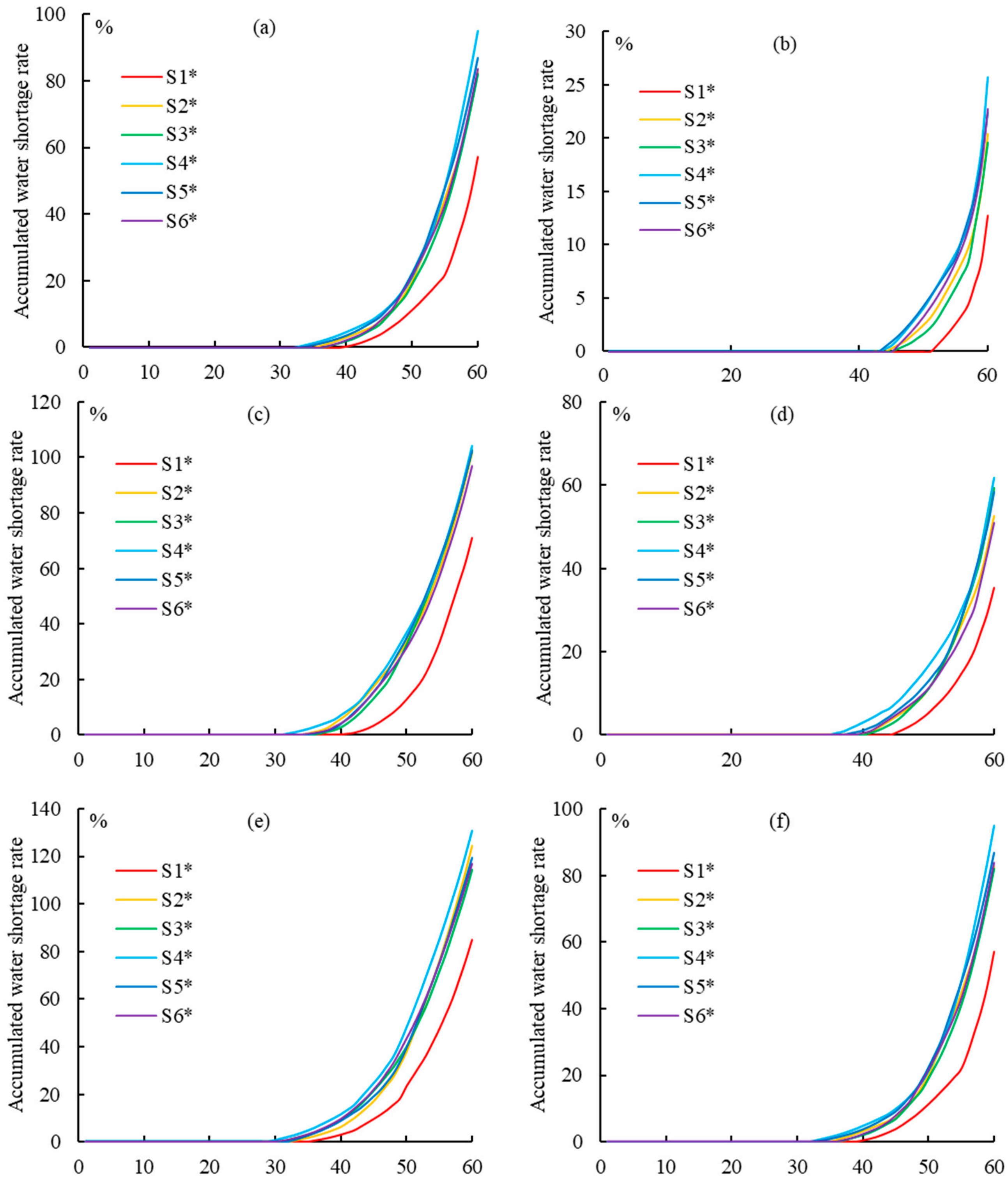

Figure 10. The annual cumulative water shortage rate curve for Unit 25 in Figure S1 with reservoir water supply sequences S1, S2, S3, S4, S5, and S6 after 500 iterations with the respective algorithm: (**a**) P1 in 2015, (**b**) P1 in 2030, (**c**) P2 in 2015, (**d**) P2 in 2030, (**e**) P3 in 2015, and (**f**) P3 in 2030. * S1 indicates the sequence of reservoir water supply (1 XLC, 2 STKM, 3 XXS), which indicates the XXS reservoir is first, the STKM reservoir is second, and the XLC reservoir is third. S2, S3, S4, S5, and S6, respectively, indicate (1 XLC, 2 XXS, 3 STKM), (1 XXS, 2 XLC, 3 STKM), (1 XXS, 2 STKM, 3 XLC), (1 STKM, 2 XXS, 3 XLC), and (1 STKM, 2 XLC, 3 XXS). The boxplot on the right shows the mean, median, outliers, and inter-quartile ranges for the annual water shortage rate of Unit 25.

Adjustable parameters affect the performance in solving optimization problems with the PSO method [35,47], especially the parameter's inertial weight, which has a profound impact on both global search ability and local search ability [48,49]. This study tested this performance by changing the value of ω in Equation (11) (Figure 11). Figure 11 shows that if the value of ω is small, the convergence speed is slow; if the value of ω is too large, it is easy to fall into the local optimum due to insufficient iterations. It reveals the above phenomenon to a certain extent.

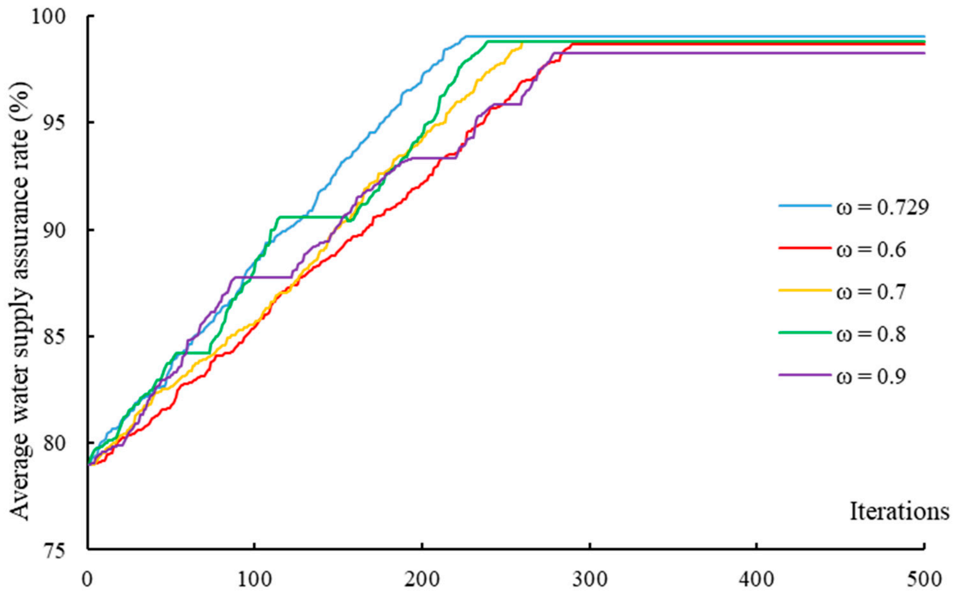

Figure 11. Convergence test of different inertial weight values.

5. Conclusions

The present study uses the YRB as an example, aiming at national economic and ecological water consumption; it also constructs a model of ROS-based multi-objective ecological operation of the reservoir group and uses the PSO method to optimise the solution. An analysis of the results is presented for the three schemes in two scenarios, and then the optimisation results of different water supply sequences in series and parallel reservoirs are compared. Finally, it is proved that different operation sequences of the reservoir groups have a great influence on the ecological operation result, and also revealed that the four operation sequences given in this study are reasonable water supply sequences for series and parallel reservoir water supply systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14106150/s1. Text S1: ROS–PSO algorithm. Figure S1: Generalised figure of reservoir group operation in YRB. Table S1: Parameters of reservoirs in YRB. Table S2: Identification table of generalized project of ecological operation model in YRB. Table S3: Prediction of annual water demand at different levels in YRB.

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