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Integrated Software Development and Case Studies for Optimal Operation of Cascade Reservoir within the Environmental Flow Constraints

Chengjun Wu [1,*], Guohua Fang [1,*], Tao Liao [2], Xianfeng Huang [1] and Bo Qu [3]

1. College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China; hxfhuang2005@163.com
2. Nanjing Branch of Jiangsu Institute of Water Resources Survey and Design, Nanjing 210000, China; ahtt4913@126.com
3. Yellow River Institute of Hydraulic Research, Zhengzhou 450003, China; qubo_edu_hohai@163.com

* Correspondence: 170202050002@hhu.edu.cn (C.W.); hhufgh@163.com (G.F.)

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Abstract: Reservoir optimal operation considering aquatic ecological protection is a hot topic in current research. This paper proposes an improved minimum monthly average runoff method (IMMR) for calculating environmental flow and an improved invasive weed optimization algorithm (IIWO) for optimizing complex problems. An integrated software consists of three modules, which is developed in this paper, i.e., IIWO convergence test module, environmental flow calculation module, and cascade reservoir operation module. Three test functions are included in the IIWO convergence test module. The minimum monthly average runoff method (MMR), IMMR, Tennant Method, Q90, and Q95 are included in the environmental flow calculation module. The IIWO and invasive weed optimization algorithm (IWO) are included in the cascade reservoir operation module. Wujiang River Basin in China is studied as a case in this paper. The results show that the environmental flow of cascade reservoir calculated by IMMR is 1871 m^3/s, the maximum and the minimum are calculated by T-O and T-M, respectively. The power generation of cascade reservoir calculated by IWO is less than IIWO. The conclusions that IIWO has better convergence than IWO in solving cascade reservoir model, and the water volume of environmental flow has no obvious influence on cascade reservoir operation are drawn.

Keywords: environmental flow; improved algorithm; reservoir optimal operation; invasive weed optimization; convergence

1. Introduction

The development and utilization of clean renewable energy is the basic requirement to reduce environmental problems and realize sustainable development [1]. Hydropower, as a renewable energy, has developed rapidly in China in recent decades [2]. However, due to the lack of management, the phenomenon of surplus water occurs frequently and the utilization rate of water is low. Moreover, due to the influence of reservoir construction, the connectivity between upstream and downstream of the river is reduced, and the water ecological protection problem is prominent [3]. Reservoir optimal operation considering ecological protection has become a hot topic in current research [4,5].

The problem of reservoir optimal operation has been studied for a long time by many researchers. In general, the research on reservoir optimal operation has gone through the process from single reservoir to multiple reservoirs [6,7]. According to the location of each reservoir, multi-reservoir is subdivided into cascade reservoir, parallel reservoir, and complex reservoir. Cascade reservoir is the most common type for a river basin. The optimization techniques for solving the problem of reservoir optimal operation are experiencing a process from classical to intelligent. Classical optimization methods include those of dynamic programming (DP) [6], large-scale system analysis [8], linear programming (LP) [9], and non-linear programming (NLP) [10], as well as those of discrete differential dynamic programming (DDDP) [11], dynamic programming with successive approximation (DPSA) [12], and progressive optimality algorithm (POA) [13]. With the development of computer technology, intelligent algorithms have developed rapidly. The most representative intelligent algorithms include genetic algorithms (GA) [14,15], particle swarm optimization (PSO) [16], and ant colony optimization (ACO) [17].

The invasive weed optimization algorithm (IWO) is a new intelligent algorithm, which is a novel numerical optimization algorithm inspired from weed colonization [18]. IWO has been applied to many fields since it was proposed due to its simplicity and good performance, such as the design of antenna arrays [19], large-scale economic problems [20], water resource management [21,22], power plant stochastic scheduling problems [23], digital terrain model extraction problems [24], bacterial colony classification problems [25], and robot motion planning problems [26]. However, due to the effect of some parameters' calculation methods (such as the standard deviation) and iterative methods of the algorithm, it is easy for IWO to fall into local optimization, especially in solving large-scale multi-constraint optimization problems. To overcome this problem, this paper proposes an improved invasive weed optimization algorithm (IIWO). The improvements are to change the spatial dispersal formula and choose an appropriate spatial dispersal rule.

With the improvement of the understanding of ecological protection, the environmental flow (also known as ecological flow) is usually used as one of the water release constraints. More than 240 environmental flow calculation methods have been proposed and applied worldwide, which can be divided into hydrological methods, habitat assessment methods, hydraulic methods, and holistic methods [27,28]. The representatives of hydraulic methods include wetted Perimeter Method and R2CROSS. Since the shape of natural river bed is not stable, it is difficult to apply the hydraulic method universally [29]. Instream Flow Incremental Methodology (IFIM) and Physical Habitat Simulation System (PHABSIM) are the representative of habitat assessment method. The Building Block Methodology (BBM) and Downstream Response to Imposed Flow Transformation (DRIFT) are the representative of holistic methods. The habitat assessment methods and the holistic methods are not commonly used since both of them need the details of aquatic ecosystems and it is complicated to use them to calculate the environmental flow [30–32]. It's easy and convenient to use Hydrological methods to calculate the environmental flow and they have been the most used methods in calculating the environmental flow. The typical hydrological methods include Tennant Method [33], Minimum Monthly Average Runoff Method (MMR) [34], Flow Duration Curve Methods (FDC, i.e., Q90 or Q95) [35], Range of Variability Approach (RVA), etc. Although the process of calculating environmental flow using MMR is convenient, the calculating result of MMR is a constant and this is not consistent with the characteristics of natural runoff, so an improved MMR (IMMR) is proposed in this paper. IMMR contains two improvements, that is, division of different years and division of different periods in one year to adapt to the periodicity of river.

The remainder of this paper is organized as follows. Section 2 outlines the cascade reservoir optimal operation model under the constraint of environmental flow, while Section 3 introduces the methodology, where the improved minimum monthly average runoff method (IMMR), the improved invasive weed optimization algorithm (IIWO), and development of integrated software are described in detail, respectively. Subsequently, case studies are presented in Section 4. Section 5 is devoted to the presentation and discussion of results, and Section 6 draws the conclusion of the paper.

2. Cascade Reservoir Optimal Operation Model under the Constraint of Environmental Flow

Cascade reservoir refers to reservoir groups consisting of two or more reservoirs on a river. There are hydraulic connections between the cascade reservoir. The hydraulic connections can be defined by Equation (1).

$$Q_{in}^{i} = Q_{r}^{i-1} + Q_{itv}^{i\sim i-1} \tag{1}$$

where Q_{in}^{i} is the inflow of the *i*-th reservoir. Q_{r}^{i-1} is the water release of the *(i-1)*-th reservoir. $Q_{itv}^{i\sim i-1}$ is the interval inflow between the *i*-th reservoir and the *(i-1)*-th reservoir.

Hydrological methods (such as Tennant method) are the most widely used method to calculate environmental flow. Since flow data is the basic data when using hydrological methods, according to Equation (1), the environmental flow in the downstream of each cascade reservoir increases successively from upstream to downstream due to the existence of interval inflow.

Cascade reservoir can realize joint optimal operation through hydraulic connections. Taking the maximum power generation of cascade reservoir as an example, it can be expressed mathematically by Equation (2).

$$maxE_c = \sum_{i=1}^{Num} \sum_{t=1}^{T} k_i \cdot Q_{e,i,t} \cdot h_{i,t} \cdot \Delta t \tag{2}$$

subject to Equation (1) and the following constraints

$$V_{t+1}^{i} = V_{t}^{i} + \left(Q_{in,t}^{i} - Q_{r,t}^{i}\right) \cdot \Delta t, \quad t = 1, 2, \cdots, T \tag{3}$$

$$Q_{r,i,t}^{min} \le Q_{r,t}^{i} \le Q_{r,i,t}^{max}, \ t = 1, 2, \cdots, T \tag{4}$$

$$Q_{r,i,t}^{min} = Q_{EF,i,t} + Q_{other}^{min}, t = 1, 2, \cdots, T \tag{5}$$

$$Z_{i,t}^{min} \le Z_{t}^{i} \le Z_{i,t}^{max}, t = 1, 2, \cdots, T \tag{6}$$

$$N_{i,t}^{min} \le N_{t}^{i} \le N_{i,t}^{max}, t = 1, 2, \cdots, T \tag{7}$$

where E_c is the power generated by the cascade reservoir hydroelectric plants; *Num* is the number of cascade reservoir in the system; *T* is the number of periods; k_i is the efficiency coefficient of the *i*-th hydroelectric plant; $Q_{e,i,t}$ is the power generation flow of the *i*-th hydroelectric plant at period *t*; $h_{i,t}$ is the effective head of the *i*-th hydroelectric plant at period *t*; Δt is the number of hours at period *t*; $Q_{in,t}^{i}$ and $Q_{r,t}^{i}$ are, respectively, the inflow and water release of the *i*-th reservoir at period *t*; V_{t+1}^{i} and V_{t}^{i} are, respectively, the water storage of the *i*-th reservoir at period *t+1* and period *t*; $Q_{r,i,t}^{min}$ and $Q_{r,i,t}^{max}$ are, respectively, the minimum and the maximum water release of the *i*-th reservoir at period *t*; $Q_{EF,i,t}$ is the environmental flow of the *i*-th reservoir at period *t*; Q_{other}^{min} is the minimum flow to meet the other water demand; $Z_{i,t}^{min}$ and $Z_{i,t}^{max}$ are, respectively, the minimum and the maximum water levels of the *i*-th reservoir at period *t*; and $N_{i,t}^{min}$ and $N_{i,t}^{max}$ are, respectively, the minimum power output and the installed capacity of the *i*-th hydroelectric plant at period *t* (MW).

3. Methodology

3.1. Improved Minimum Monthly Average Runoff Method (IMMR)

It is necessary for the environmental flow to maintain a healthy ecosystem and sustain aquatic life. The environmental flow is different in different periods. The minimum monthly average runoff method (MMR) has been frequently used to analyze the environmental flow. It can be shown as Equation (8).

$$Q = \frac{1}{n} \sum_{i=1}^{n} min\left(Q_{ij}\right) \tag{8}$$

where n is the number of years, and Q_{ij} is the monthly average runoff in month j of the i-th year.

As shown in Equation (8), the environmental flow calculated by MMR is a constant. This is not consistent with the characteristics of environmental flow. The IMMR is proposed to adapt to the periodicity of river, which consists of the following three steps.

3.1.1. Divide into Different Years

The years are divided into high flow years, normal flow years, and low flow years. These three types are usually divided by different guarantee rates. However, there is a certain subjectivity as to how much the guarantee rate meets the requirements of the division. Thus, a method called Percentage From Mean (PFM) is used to overcome the defect.

$$\mu = (Q_i - Q_a)/Q_a \times 100\% \tag{9}$$

where μ is the percentage from mean; Q_i is the average runoff in the i-th year; and Q_a is the multi-year average runoff.

3.1.2. Division of Different Periods in One Year

Similar to the first step, the PFM is also used to divide the different periods in one year. The dividing equation is shown as Equation (10).

$$\mu_j = \left(Q_j - Q_a\right)/Q_a \times 100\% \tag{10}$$

where μ_j is the percentage from mean of month j, and Q_j is the multi-year average runoff of month j.

The division criteria for different years and different periods in one year are presented in Table 1.

Table 1. Division criteria for different years and different periods in one year.

Percentage from Mean	High Flow Year (Flood Season)	Normal Flow Year (Flat Period)	Low Flow Year (Dry Season)
μ	$\mu > 20\%$	$-20\% < \mu \le 20\%$	$\mu \le -20\%$
μ_j	$\mu_j > 20\%$	$-20\% < \mu_j \le 20\%$	$\mu_j \le -20\%$

3.1.3. IMMR for Environmental Flow

Similar to Equation (8), the equation of IMMR for environmental flow is presented as Equation (11).

$$Q_b = \frac{1}{n_b}\sum_{a=1}^{n_b} min(Q_{ab}), \quad b = 1,2,3 \tag{11}$$

where b = 1,2,3 represent high flow year, normal flow year, and low flow year, respectively. Q_b (b = 1, 2, 3) represent flood season, flat period, and dry season, respectively. $Min(Q_{ab})$ is the minimum monthly average runoff in a-th year of b. n_b is the number of years of b.

3.2. Improved Invasive Weed Optimization Algorithm (IIWO)

3.2.1. Invasive Weed Optimization Algorithm (IWO)

IWO is a numerical stochastic optimization algorithm, which is inspired from colonizing weeds. The IWO algorithm mainly includes four steps: initializing a population, reproduction (as shown in Equation (12)), spatial dispersal, and competitive exclusion (retain pre-determined maximum populations of weeds whose fitness value is better than others). In the third step, the seeds generated in the second step are randomly distributed in the space of feasible region as a normal distribution with mean equal to zero (as shown in Equation (13)). As well, the variance of the normal distribution is calculated by Equation (14).

$$Seed(i) = int\left\{\frac{F(i) - F_{min}}{F_{max} - F_{min}} \cdot (Seed_{max} - Seed_{min}) + Seed_{min}\right\} \tag{12}$$

$$X_{i,s} = X_i + N\left(0, \sigma_{iter}^2\right) \tag{13}$$

$$\sigma_{iter} = \sigma_{fin} + \left(\frac{iter_{max} - iter}{iter_{max}}\right)^w \left(\sigma_{ini} - \sigma_{fin}\right) \tag{14}$$

where *Seed(i)* is the number of seeds reproduced by the *i*-th weed; *int (X)* is the integral function expressing the integer part of the real number X (i.e., the largest integer smaller than X); *F(i)* is the individual fitness value of the *i*-th weed; F_{max} and F_{min} are, respectively, the maximum and the minimum fitness values of the population; $Seed_{max}$ and $Seed_{min}$ are the maximum and minimum numbers of seeds that can be reproduced by weed, respectively; X_i is the position of the *i*-th weed; $X_{i,s}$ is the position of the *s*-th seed reproduced by the *i*-th weed; $N\left(0, \sigma_{iter}^2\right)$ is a normal distribution with a zero mean and a standard deviation of σ_{iter}, which is the standard deviation at the present time step; w is a nonlinear modulation index ($w = 3$); σ_{ini} and σ_{fin} are previously defined initial and final standard deviations ($\sigma_{ini} > \sigma_{fin}$); and $iter_{max}$ is the maximum number of iterations.

IWO has a "global-local" optimization mechanism according to Equations (13) and (14), but it still has a defect in solving high-dimensional, nonlinear, and multi-constrained problems. The shortcoming of IWO is that it is easy to fall into local optimum. Therefore, it is necessary to improve IWO for solving large and complex problems more effectively.

3.2.2. Improvement from IWO to IIWO

Improvement of Spatial Dispersal Formula

Since trigonometric functions have periodic properties, Equation (14) is improved to Equation (15).

$$\sigma_{iter} = \sigma_{fin} + cos\left(\frac{iter}{iter_{max}} \cdot \frac{(2n+1)\pi}{2}\right)^2 \left(\sigma_{ini} - \sigma_{fin}\right),\ n = 1, 2, \cdots \tag{15}$$

by comparing Equations (14) and (15), IIWO has the features of periodic optimization and has better performance, since it breaks through the constraint of local optimization, and achieves global optimization more easily. Figure 1 shows a pseudo simulation diagram of the optimization process of IWO and IIWO. Its purpose is to show the difference between IWO and IIWO more vividly.

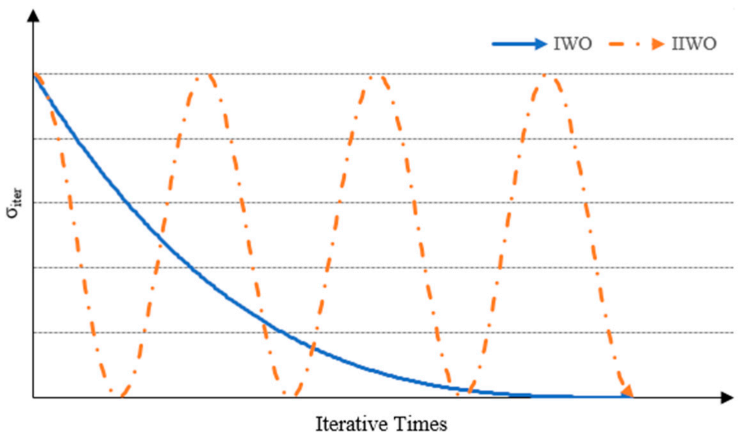


Figure 1. Pseudo simulation diagram of the optimization process of IWO and IIWO.

Selection of Spatial Dispersal Rules

According to the principle of IWO, four dispersal rules are theoretically included in the process of spatial dispersal, which are for iterations, weeds, seeds, and eigenvector, respectively. The four rules can be seen in Figure 2.

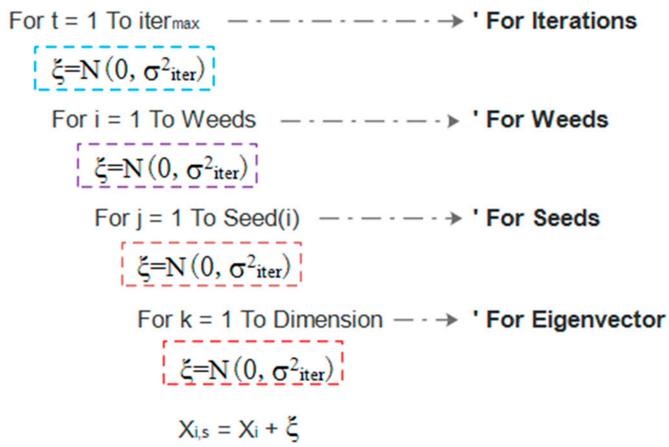


Figure 2. Four dispersal rules included in IWO.

The rules for iterations, weeds, and seeds are isotropic realizations of IWO. Under these three rules, the same normal random variable has been used for each dimension. Thus, it is bad for the diversity of the population, and it is difficult to find the global optimal solution. However, the rule for eigenvector is an anisotropic realization, because a new normal random variable is generated for each dimension. As well, in this way the diversity of the population can be increased. In theory, this rule can be used to find the global optimization more possibly.

The Schaffer function is used to compare these four rules in this paper. As well, the optimization results are shown in Figure 3.

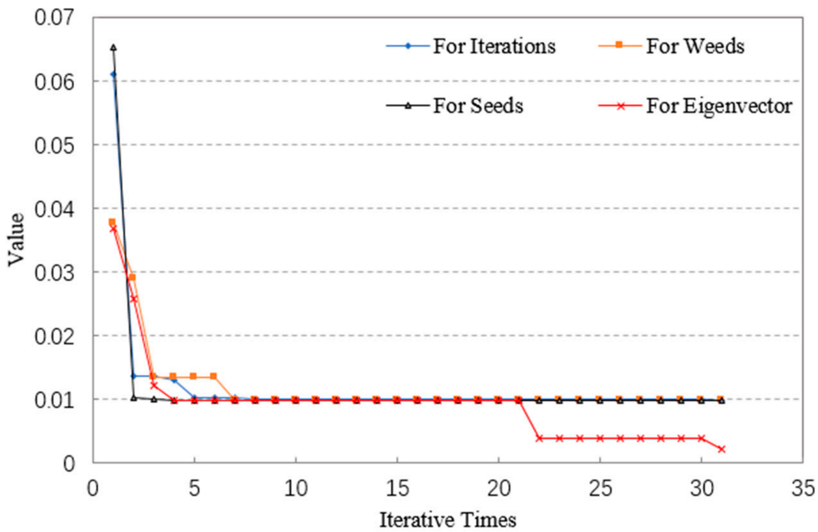


Figure 3. Four dispersal rules included in IWO.

Figure 3 shows that the dispersal rule for eigenvector is indeed better than the other three dispersal rules in finding the global optimization. Therefore, it is essential to take "eigenvector" as the dispersal rule in solving high-dimensional, nonlinear, and multi-constrained problems.

3.3. Development of Integrated Software

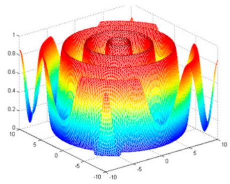
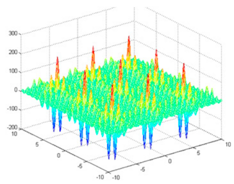
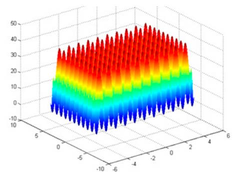
The software is developed based on Visual Basic 6.0. Its development environment is on an Intel(R) Xeon(R) machine with an E5620 CPU @2.40GHz, RAM of 4.00GB, and a 64-bit operating system. The operation results are output to EXCEL. The software supports the version of Microsoft Office from 07 to 16.

The integrated software consists of three modules, i.e., the IIWO convergence test module, the environmental flow calculation module, and the cascade reservoir operation module.

3.3.1. IIWO Convergence Test Module

In this module, three functions are used to test the convergence of IIWO: Schaffer, Shubert, and Rastrigin (as shown in Table 2).

Table 2. Optimization test functions.

Name	Formula	Sketch
Schaffer	$f(x) = 0.5 + \frac{\left(\sin\sqrt{x_1^2+x_2^2}\right)^2 - 0.5}{\left[1+0.001\left(x_1^2+x_2^2\right)\right]^2}$	
Shubert	$f(x) = \left\{\sum_{i=1}^{5} i\cos[(i+1)x_1+i]\right\} \cdot \left\{\sum_{i=1}^{5} i\cos[(i+1)x_2+i]\right\}$	
Rastrigin	$f(x) = \sum_{i=1}^{D}\left[x_i^2 - 10\cos(2\pi x_i) + 10\right]$	

Schaffer function is a two-dimensional complex function, which has countless minima points and gets the minimum value of 0 at (0, 0). In this module, both independent variables (i.e., x_1 and x_2) in this function have a range of values [−10, 10]. *Sin()* is sine function.

Shubert function is also a two-dimensional complex function, which has 760 local extreme points. This function gets the minimum value of −186.7309 at (−1.42513, 0.80032). In this module, both independent variables (i.e., x_1 and x_2) in this function also have a range of values [−10, 10]. *Cos()* is cosine function. i is an integer.

Rastrigin function is a typical nonlinear multimodal function, whose peak shape is characterized by fluctuation and jump. This function gets the minimum value of 0 at (0, 0, . . . , 0). In this module, D is the dimension of the function. Here, D is set to 2, and the independent variables (i.e., x_i) have a range of values [−5.12, 5.12]. Here, π = 3.1415926.

In this module, the parameters of IIWO are set as follows: P_{ini} = 20 (the initial weeds population), P_{fin} = 90 (the maximum weeds population), $Seed_{max}$ = 5, $Seed_{min}$ = 2, σ_{ini} = 2, σ_{fin} = 0.001, $iter_{max}$ = 60, and n = 3 (in Equation (15)).

3.3.2. Environmental Flow Calculation Module

Five methods for calculating environmental flow have been integrated in this module. They are IMMR, MMR, Tennant, Q90, and Q95 respectively. In addition, five flow conditions are included in the

Tennant method. The five flow conditions of Tennant method are outstanding, excellent, good, fair or degrading, and poor or minimum. The specific contents of the five flow conditions are shown in Table 3.

Table 3. Five flow conditions of Tennant method.

Flow Condition	October-March	April-September
Outstanding	40% average annual flow	60% average annual flow
Excellent	30% average annual flow	50% average annual flow
Good	20% average annual flow	40% average annual flow
Fair or degrading	10% average annual flow	30% average annual flow
Poor or minimum	10% average annual flow	10% average annual flow

3.3.3. Cascade Reservoir Operation Module

IWO and IIWO are both integrated in this module. The parameters of IWO and IIWO are shown as follows: P_{ini} = 20, P_{fin} = 90, $Seed_{max}$ = 5, $Seed_{min}$ = 2, σ_{ini} = 2, σ_{fin} = 0.001, $iter_{max}$ = 60, w = 3 (in Equation (14)), and n = 3 (in Equation (15)). The environmental flow calculated by each method mentioned above is used as the constraint of water release to optimize both single reservoir and cascade reservoir operation, respectively.

The runoff forecasting accuracy is relatively low under current conditions. Runoff forecast results are constantly being revised. Due to the uncertainty of the inflow, the theoretical results of reservoir optimal operation cannot be applied to actual scheduling well, especially to the cascade reservoirs. A rolling correction mechanism is developed in this module to adapt to the change of runoff forecast. Taking one year as an operation cycle as an example, the formulation and revision processes of its operation curve are as follows:

Step 1. Generate initial operation curve. The initial operation curves are generated using IIWO according to the forecast results of monthly runoff during one year. Here, the maximization of the generated power is served as the objective function;

Step 2. Revise the initial operation curve. Ignore the months that have completed operation, and the remaining months are used as a new operation cycle. Operation curves of the remaining months are regenerated using IIWO based on the revised runoff forecast results.

4. Case Studies

We analyze the operation of a cascade reservoir in Wujiang River Basin, located in Guizhou Province in China (shown in Figure 4). As well, Wujiang cascade reservoir is mainly for power generation. Wujiang River is a tributary of the Yangtze River, with a basin area of 87,900 km^2. We consider here two cascade reservoirs in the upper reaches of Wujiang River, i.e., Hongjiadu Reservoir and Dongfeng Reservoir.

Hongjiadu Reservoir represents a carry-over storage, while Dongfeng Reservoir is an incomplete annual regulation reservoir. The flood season for each reservoir is from June to September every year. The characteristic parameters of each reservoir are shown in Table 4.

The starting water levels of Hongjiadu and Dongfeng reservoirs are set at 1084 m and 960 m, respectively. Meanwhile, for each reservoir, the starting and ending water levels are the same.

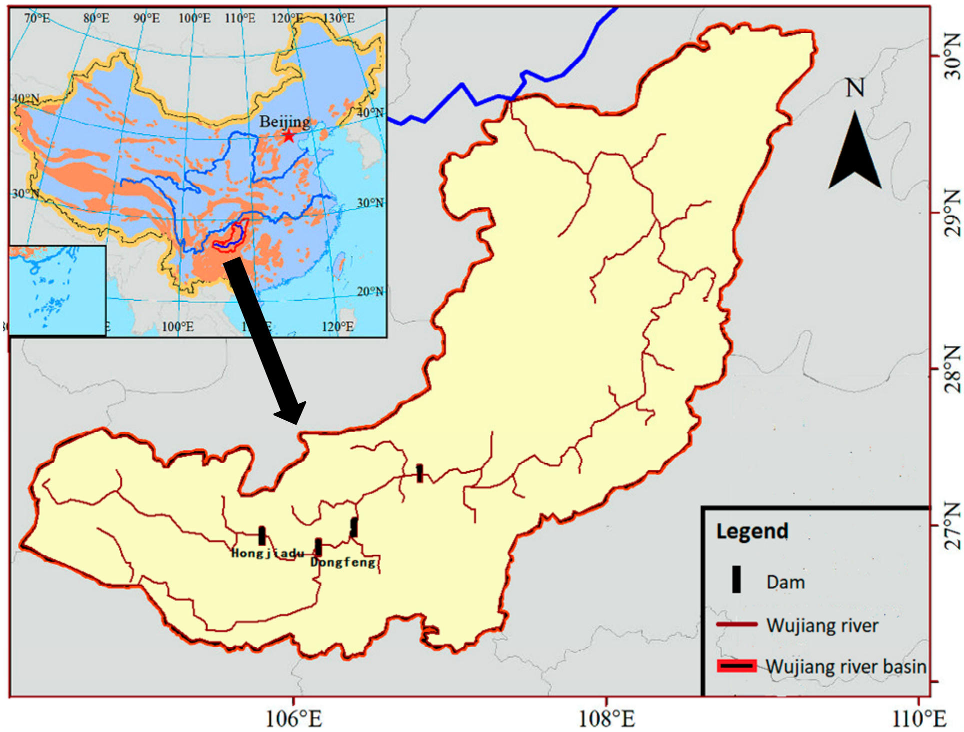
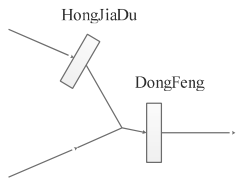


Figure 4. The sites of Hongjiadu and Dongfeng on Wujiang River and the location of Wujiang river basin in China.

The runoff data of Wujiang River Basin from 1977 to 2015 are used to calculate the environmental flow. Due to the interval inflow between Hongjiadu and Dongfeng reservoirs, the environmental flow of both reservoirs are calculated. The methods for calculating environmental flow are all used here. The environmental flow of both Hongjiadu and Dongfeng is used as the two reservoirs discharge constraints, respectively.

Table 4. Characteristic parameters of the cascade reservoir of Wujiang River Basin.

Name	Hongjiadu	Dongfeng	Location Diagram of the Two Reservoirs
Normal water level (m)	1140	970	
Flood control level (m)	1138	970	
Dead water level (m)	1076	936	
Guaranteed output (MW)	159.1	100	
Installed capacity (MW)	600	695	
Efficiency coefficient	8.4	8.35	

The runoff data of high flow year (1990), normal flow year (2000), and low flow year (1995) (shown in Figure 5a,b) are used as the inflow data to optimize both the single reservoir (Hongjiadu) and the joint operation model of the cascade reservoir, respectively. The above three cases are solved by IIWO. Meanwhile, in order to compare the efficiency of IWO and IIWO, when using the runoff data of high flow year, IWO is also used to solve this case.

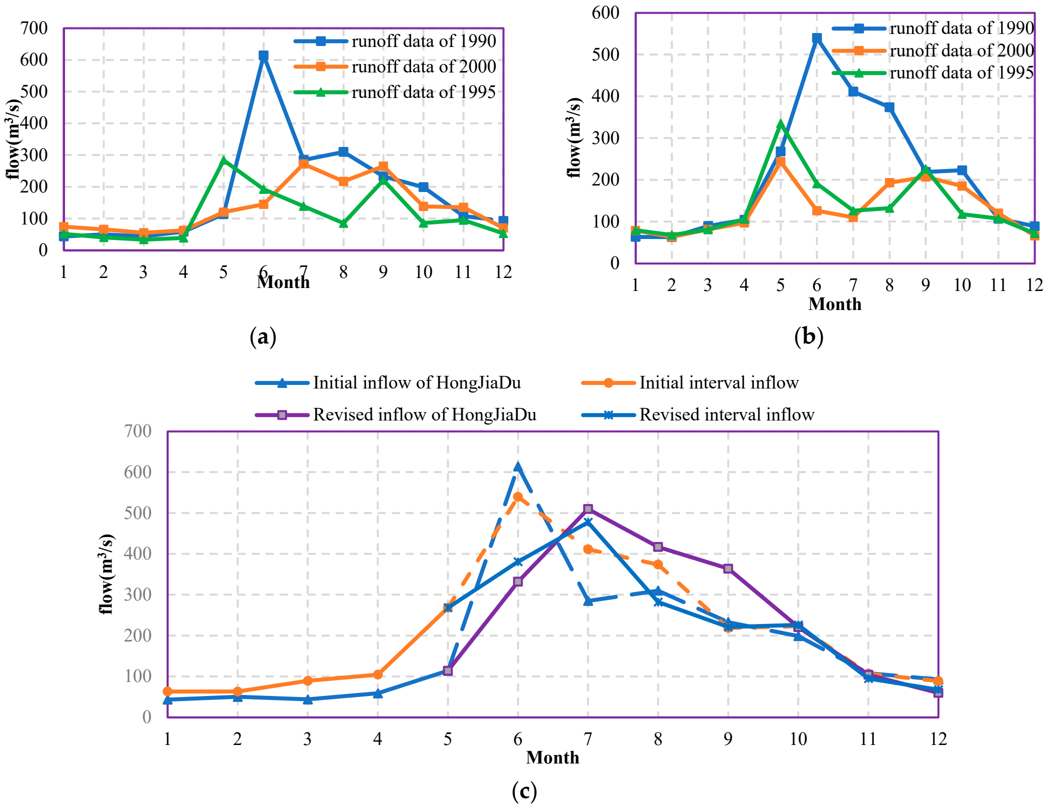


Figure 5. Monthly runoff data of Wujiang River Basin and its monthly runoff forecast results of 2019: (**a**) Inflow of Hongjiadu; (**b**) interval inflow between Hongjiadu and Dongfeng; (**c**) the initial forecast monthly runoff data of 2019 and its revised results.

The monthly runoff forecast results of 2019 (shown in Figure 5c) are used as the inflow data to optimize the joint operation model of the cascade reservoir. Meanwhile, taking the environmental flow calculated by IMMR as water release constraint, the cascade reservoir operation curves are rolled over based on the revised monthly runoff forecast results of 2019. This case is solved by IIWO.

5. Results and Discussion

5.1. IIWO Convergence Test

After 60 iterations, Schaffer, Shubert, and Rastrigrin functions finally converge to 0.00057, −186.553, and 0.005834, respectively. Convergences of IIWO to Schaffer, Shubert, and Rastrigrin are shown in Figure 6.

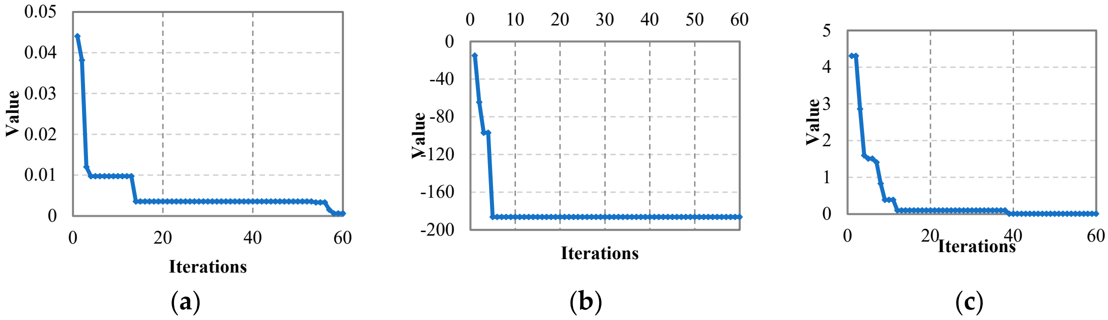


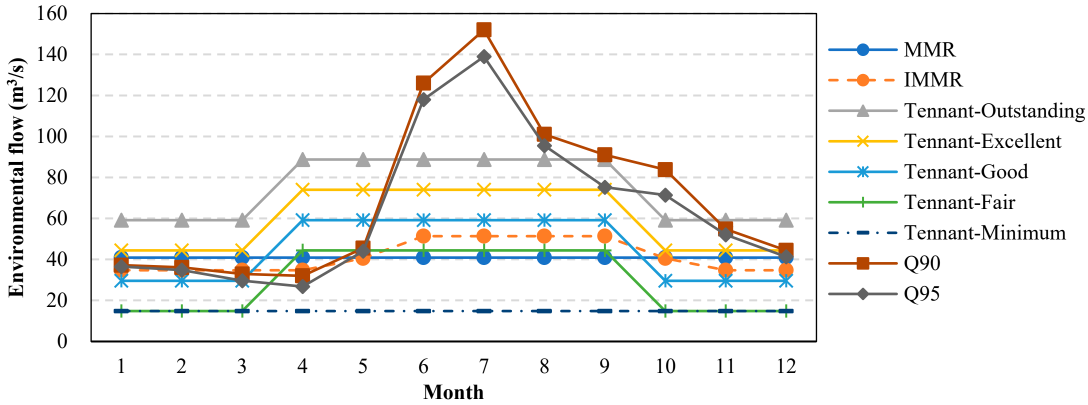
Figure 6. Convergences of IIWO to Schaffer, Shubert, and Rastrigrin: (**a**) Convergence of IIWO to Schaffer; (**b**) convergence of IIWO to Shubert; (**c**) convergence of IIWO to Rastrigrin.

This figure shows that, in the early stage of the optimization process, the algorithm can quickly converge to a value close to the optimal value. In the middle and late optimization stages, although the algorithm converges to a certain local optimal solution repeatedly in different iteration periods, it can escape the local optima and gradually reach the global optimum in the subsequent iterations. All in all, IIWO has a good convergence when dealing with complex functions.

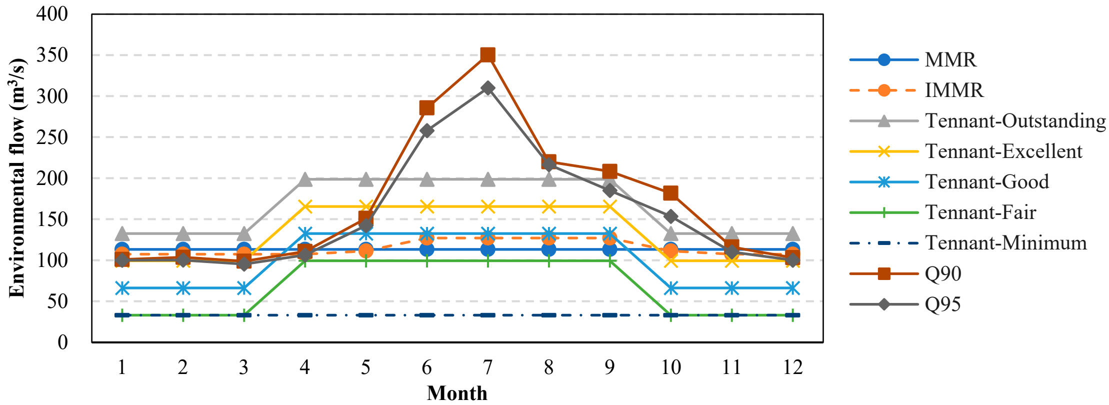
5.2. Environmental Flow Calculation

The division results of different periods in one year calculated by IMMR are as follows: The flood season is from June to September; the dry season is from November to April; and the flat period includes May and October.

The environmental flows of Hongjiadu and Dongfeng calculated by different methods are shown in Figure 7 and Table 5.



(**a**)



(**b**)

Figure 7. Environmental flow of Hongjiadu and Dongfeng: (**a**) Environmental flow of Hongjiadu; (**b**) environmental flow of Dongfeng.

Table 5. Total environmental flow during the year (m^3/s).

Reservoir	IMMR	MMR	Q90	Q95	T-O	T-E	T-G	T-F	T-M
Hongjiadu	495	491	837	764	888	710	533	355	178
Dongfeng	1376	1360	2031	1877	1988	1590	1193	795	398
Total	1871	1851	2868	2641	2876	2300	1726	1150	576

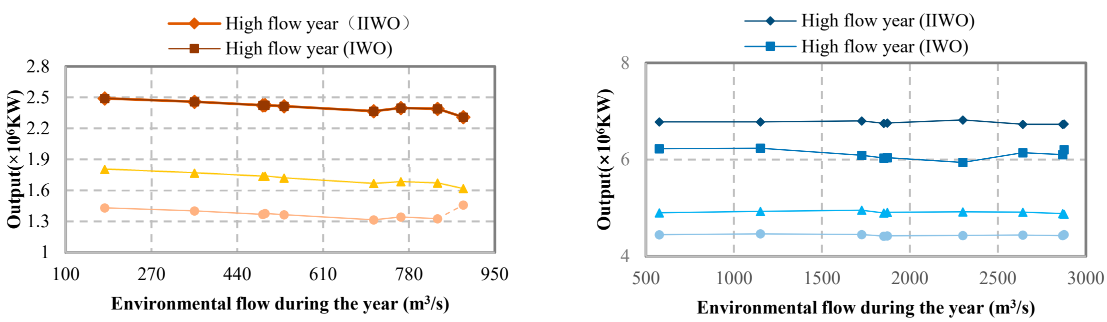
In Table 5, T-O, T-E, T-G, T-F, and T-M represent outstanding, excellent, good, fair, and minimum conditions of Tenant method, respectively. The environmental flow during the year calculated by IMMR is greater than that by MMR, T-G, especially T-F and T-M, but lower than that of Q90, Q95, T-O, and T-E. Overall, IMMR is reasonable in calculating the water volume of environmental flow during the year.

Figure 7 shows that the environmental flow of Dongfeng is greater than that of Hongjiadu during the same period. The interval inflow between Hongjiadu and Dongfeng is the reason for the above result. Meanwhile, as we can see, the environmental flow in April calculated by Q90 and Q95 is less than the results of other methods. This is inconsistent with the rule that the environmental flow in flat period is larger than that in dry season. In addition, the environmental flow in flood season is much greater than other methods. In other words, there are limitations in calculating environmental flow by using Q90 or Q95 alone. The environmental flow calculated by IMMR is slightly lower than the result of T-G during the flood season, but larger than that of T-G during the dry season. Meanwhile, the environmental flow calculated by IMMR in most months is greater than the results of T-F, and the results of IMMR in every month are all larger than the results of T-M. The environmental flow calculated by IMMR in different months reflects the characteristics that the environmental flow in different periods is different, and the monthly environmental flow calculated by IMMR is between the results for other methods. Therefore, IMMR is more reasonable than MMR in calculating environmental flow.

5.3. Single Reservoir and Cascade Reservoir Optimal Operation

5.3.1. Operation Results in Different Years

The impacts of the environmental flow calculated by different methods on both single-reservoir operation and cascade reservoir operation are shown in Figure 8.



(**a**) (**b**)

Figure 8. Impacts of different environmental flows on reservoir operation (using the annual environmental flow and annual output as statistical data): (**a**) Impacts of different environmental flows on single-reservoir operation (Hongjiadu); (**b**) impacts of different environmental flows on cascade reservoir operation (Hongjiadu and Dongfeng).

It is worth pointing out that there are three hollow data points in Figure 8. All of them occur under the condition that the environmental flow calculated by T-O is used as the water release constraints. These three points mean that the inflow cannot meet the discharge constraints for all months. At least, using IIWO (or IWO) cannot find the optimal reservoir operation scheme that can satisfy all monthly environmental flow constraints.

Figure 8a shows that, for a single reservoir, its power generation decreases with the increase of environmental flow as the whole. The result is similar to other research results in this field [36]. However, although the environmental flow calculated by IMMR is more than that by MMR, the optimal operation result using the environmental flow calculated by IMMR as the water release constraint is a little more than the result of MMR. Meanwhile, the optimal operation result of Q95 is more than the result of T-E while the environmental flow calculated by Q95 is more than T-E. These indicate that the effect of environmental flow on reservoir optimal operation is not only influenced by the water volume of environmental flow during the year, but also influenced by the distribution of the environmental flow during the year. Furthermore, under the condition of similar water volume of environmental flow during the year, the closer the distribution of the environmental flow is to the natural runoff process, the greater the power generation of the reservoir optimal operation will be. The environmental flow with similar distribution pattern during the year is strictly subject to the rule of decreasing power generation with the increase of water volume of environmental flow. Moreover, we can also figure out that IMMR is more reasonable than MMR in calculating the environmental flow.

In addition, according to the results of high flow year, there is no significant difference between IWO and IIWO in the efficiency of solving single-reservoir optimal operation model. It indicates that IWO and IIWO have similar abilities in solving the problems with lower dimension.

The hollow data point that appears in Figure 8a indicates that the low flow year of Wujiang River Basin cannot meet the environmental flow calculated by T-O. In other words, T-O is not applicable to this drainage basin.

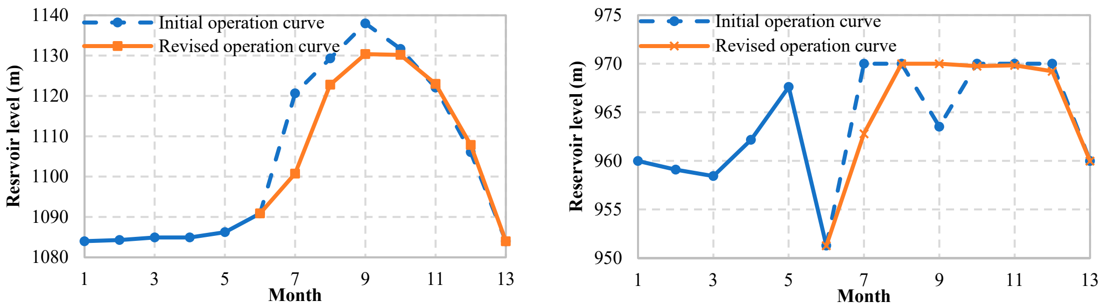
The results of cascade reservoir optimal operation for high flow year solved by IIWO and IWO in Figure 8b have a significant gap, especially for the case that the environmental flow calculated by T-O is used as water release constraint, IWO cannot find a feasible solution that can satisfy the constraint of environmental flow. These indicate that IWO has fallen into local optimality obviously when solving the cascade reservoir optimal operation model. Therefore, the ability of IWO in solving high-dimensional problems is lower than that of IIWO. Moreover, these also show that IIWO is more feasible in solving cascade reservoir optimal operation model.

At the macro level, Figure 8b also shows that the environmental flow calculated by different methods have no obvious influence on the cascade reservoir optimal operation (it means the different water volumes of environmental flow during the year and the power generation of the cascade reservoir have no obvious rivalry). As well, whether in the high flow year, normal flow year, or low flow year, the phenomena all show the same. There is no decrease in the generated energy of cascade reservoir with the increase of the water volume of environmental flow during the year, which is inconsistent with the results of other literatures. For example, a research result of cascade reservoir (i.e., the Nuozadu, Jinghong, and Ganlanba reservoirs) in Lancang River Basin in China, shows that the generated energy of cascade reservoir decreases with the increase of the water volume of environmental flow during the year [37]. According to our analysis, the reasons for this result in this paper can be summarized as the following two aspects. The first is that the interval inflow between Hongjiadu and Dongfeng is rich and cannot be ignored compared with the main river runoff (i.e., the inflow of Hongjiadu). The second is that Hongjiadu Reservoir, used as a carry-over storage, has good regulating performance. Hongjiadu has the function of runoff compensation regulation for Dongfeng Reservoir. As well, as a result of the existence of the runoff compensation regulation, the environmental flow calculated by different methods, used as the water release constraints, has inconspicuous influence on the generated energy of cascade reservoir.

Although at the macro level the environmental flow calculated by different methods has no obvious influence on the generated energy of cascade reservoir, the different distributions of the environmental flow during the year have some small effects on the generated energy of cascade reservoir at the micro level. The effects of different environmental flows on the generated energy of cascade reservoir are similar to the effects on single reservoir. That is, the closer the distribution of the environmental flow is to the natural runoff process, the greater the generated energy of cascade reservoir will be. Taking the environmental flow calculated by MMR and IMMR as an example, the generated energy of cascade reservoir using the latter environmental flow as water release constraints is larger than that using the former.

5.3.2. Rolling Correction of Cascade Reservoir Operation Curves

According to the initial forecast runoff data of 2019 and the revised forecast runoff data, the initial operation curves and the revised operation curves of Hongjiadu and Dongfeng are shown in Figure 9.



(**a**) (**b**)

Figure 9. Rolling correction of Hongjiadu and Dongfeng reservoirs dispatch curves: (**a**) Rolling correction of Hongjiadu operation curve; (**b**) rolling correction of Dongfeng operation curve.

Figure 9 shows that under the condition that the starting and ending water levels of reservoir have been determined during the operation period, and the change of forecast runoff will significantly affect or change the reservoir operation plan. Especially in the current power market environment, this will greatly affect the benefit of hydropower station. Therefore, it is necessary to continue the in-depth research on medium and long-term runoff forecast. The accuracy of medium and long-term runoff forecast must be improved. As a result, the stability of reservoir power generation will be improved and the competitiveness of hydropower stations in the power market will be increased.

6. Conclusions

An integrated development software is introduced in this paper. Two innovations are proposed and included in the software (i.e., IMMR and IIWO). The global optimal convergence performance of IIWO is preliminarily verified by optimizing three commonly used multi-peak test functions. This paper applies IMMR, MMR, Tennant, Q90, and Q95 to calculate the environmental flow of Wujiang River Basin, respectively, and discusses the results of environmental flow calculated by different methods. This paper applies IIWO and IWO to both single-reservoir operation and cascade reservoir operation with the environmental flow as water release constraint, as well as discusses the results of reservoir optimal operation therewith. From the above, we can draw the following conclusions.

The environmental flow calculated by IMMR adapts to the character of natural runoff well. It can maintain a healthy water ecosystem with a better standard compared with the results of Tennant method. Meanwhile, taking the environmental flow calculated by IMMR as water release constraint, the generated energy of both single reservoir and cascade reservoir is satisfactory compared to other results. At the same time, taking the results of environmental flow and reservoir optimal operation into consideration, T-G and Q95 also adapt to this basin.

IIWO has global optimization capability and can converge to the global optimal solution in optimizing the high-dimensional multimodal complex function. Comparing with IWO, IIWO has a better efficiency in solving the model of cascade reservoir optimal operation.

The generated energy of single reservoir is affected by both the volume of environmental flow and the distribution of environmental flow during the year. Generally, the power generation decreases with the increase of the volume of environmental flow under the condition that the annual distribution of the environmental flow is similar. Furthermore, the more the annual distribution of ecological flow with a similar volume of environmental flow during the year is close to natural runoff, the greater the power generation will be.

The environmental flow calculated by different methods has an inconspicuous effect on the power generation of cascade reservoir at the macro level. However, at the micro level, similar to single reservoir, the more the annual distribution of ecological flow is close to natural runoff, the greater the power generation will be.

Although the calculation of environmental flow, the influence of environmental flow on reservoir operation, and the rolling correction of reservoir operation are studied in this paper, the following questions need further in-depth study.

The problem of medium and long-term runoff forecast should be deeply studied to improve the accuracy of forecast runoff and the competitiveness of hydropower in the electricity market.

In order to choose a specific method for calculating environmental flow for a specific basin, a quantitative evaluation method should be studied to balance the relationship between power generation benefits of reservoir and water ecosystem protection benefits. Meanwhile, the performance of the system when applied in more reservoirs (i.e., more than 2 reservoirs) should be further studied.

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