

The optimal equilibrium operation between power generation and ecology of Qingjiang cascade hydropower stations

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Abstract. Ecological operation of cascade hydropower stations is one of the most important methods for the ecological restoration of a river system. In order to balance the benefits between power generation and ecology of Qingjiang cascade hydropower station, an optimal equilibrium operation method is proposed in this paper. Firstly, the range of ecological flow of the Qingjiang cascade is calculated by using ten-day frequency calculation method. Secondly, an optimal equilibrium operation model by considering the balance between power generation and ecology is established. And then, in order to solve this complex model, a particle swarm optimization based model solution method is proposed, and the evaluation index system of operation schemes is established. Finally, through operation calculation in 2008-2010 years, the results show that compared with the operation scheme considering only power generation benefit, the optimal equilibrium operation scheme increases the runoff ecological dispersion coefficient by 6.90%, reduces the cascade ecological overflow by 7.739 billion m³ and the cascade ecological water shortage by 130 million m³, while the cascade power generation decreases slightly by 1.83%. This study provides an effective scientific method for the optimal operation of Qingjiang cascade under the background of Yangtze River protection.

1 Introduction

In 2018, at the Second Forum on the Development of the Yangtze River Economic Zone held in Wuhan, Comrade Xi Jinping pointed out: "Correctly grasp the relationship between overall promotion and key breakthroughs, and comprehensively do a good job in the protection and restoration of the Yangtze River ecological environment. Correctly grasp the relationship between ecological environment protection and economic development, and explore a new way to promote ecological priority and green development in coordination. As the second largest tributary of the middle reaches of Yangtze River below the Three Gorges, the Qingjiang River Basin is 423 km long and consists of Shuibuya, Geheyan and Gaobazhou three large-scale hydropower stations. Shuibuya hydropower station (SBY) has the ability to regulate for many years. Geheyan hydropower station (GHY) has the ability to regulate annually. Gaobazhou hydropower station (GBZ) is a runoff-type power station with the ability of daily regulation. The storage capacity is 2.394 billion m³, 1.975 billion m³, and 50 million m³ respectively. The installed capacity is 1.84 million kwh, 1.12 million kwh and 270,000 kwh respectively. Qingjiang River Basin is an important part of ecological restoration in the Yangtze River Basin. The topological relation map of Qingjiang cascade is shown in Figure 1.

At present, scholars pay more attention to the ecological regulation of the Three Gorges-Gezhouba

cascade with the Three Gorges Reservoir as the core. In 2009, Guo et al. [1] determined the goal of reservoir ecological regulation for the Three Gorges cascade from the viewpoint of maintaining the environmental flow in the natural river channel and facilitating the spawning and reproduction of Chinese sturgeon and four big family fish in the lower reaches of the reservoir. In 2011, Lu et al. [2] established a multi-objective ecological optimal dispatching model for the Three Gorges cascade hydropower station, aiming at maximizing the generation capacity and minimizing the ecological water shortage. And the eco-friendly multi-objective optimal dispatching model of the Three Gorges cascade hydropower station was constructed by Wang et al. [3] in 2013. In 2017, Dai et al. [4] introduced the non-dominated sequencing genetic algorithm with elite retention strategy to solve the reservoir optimal operation model with the objective of maximizing the generating capacity of the Three Gorges hydropower station and minimizing the change of the optimal ecological flow in the downstream river.

However, there is little research on Qingjiang cascade related ecological dispatch, and more attention is paid to the problem of ecological base flow (minimum ecological flow)[5]. In this paper, the optimal equilibrium operation between power generation and ecology carried out by considering the change range method (RVA) [6], based on the ten-day frequency calculation method and combining particle swarm optimization algorithm is of great practical significance.

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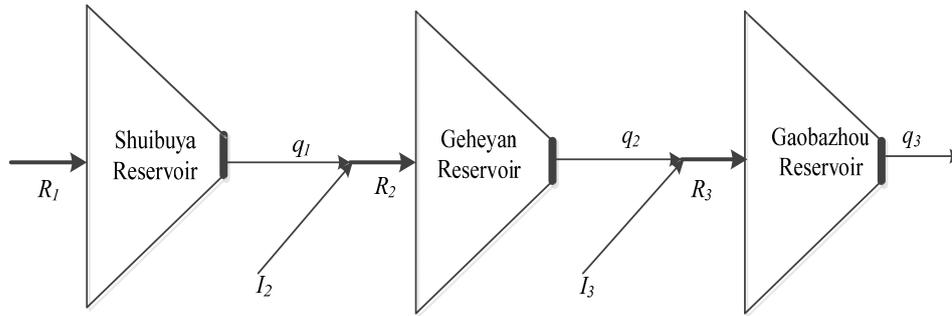


Fig. 1. The topological relation map of Qingjiang cascade

Notes: R_i is inflow of the i th reservoir; q_i is the water release of the i th reservoir; I_i is the stream flow of intermediate catchment between the $i-1$ th reservoir and the i th reservoir.

2 Calculation of Qingjiang cascade ecological flow

Generally speaking, the initial year of river ecological environment stress is the year of dam construction on river reference section, and the first dam of Qingjiang cascade hydropower station was GHY, which was started in January 1987. Taking year 1987 as the demarcation line before and after ecological environment stress, the historical hydrological series of Qingjiang River is divided into two parts: natural state (1951-1986) and stress state (1987-2010). The P-III distribution was used to analyze the hydrological frequency of the average runoff of Qingjiang cascade hydropower stations in natural state (1951-1986). According to the RVA framework, 70% frequency of a period of ten days corresponding to the flow process was taken as the lower limit of the ecological suitable flow, and 30% frequency of a period of ten days corresponding to the flow process was taken as the upper limit of ecological suitable flow. At the same time, the flow processes corresponding to the two extreme frequencies of 90% and 10% are taken as the minimum ecological flow constraint and the maximum ecological flow constraint, respectively^[7]. The ecological flow process of each hydropower station is shown in Figure 1.

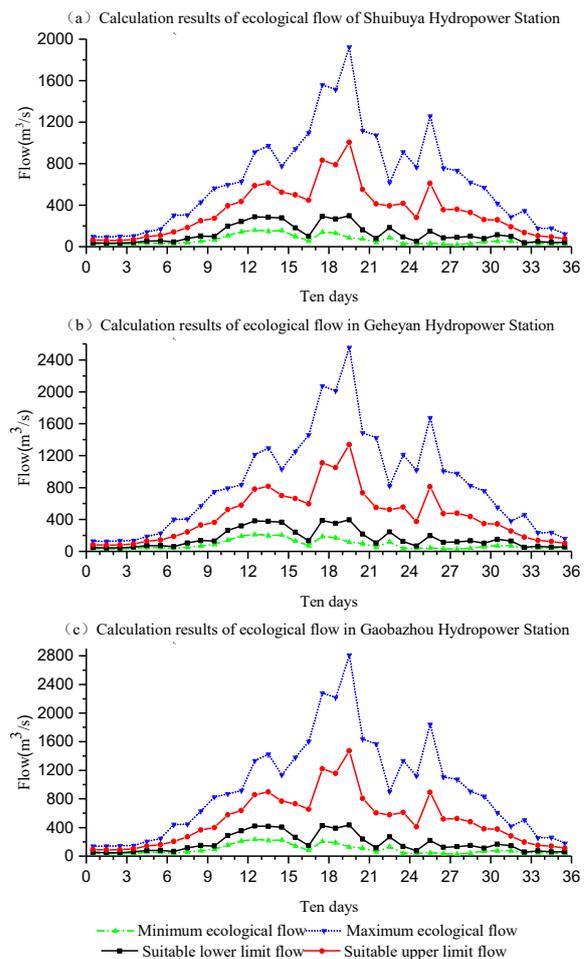


Fig. 2. Calculation results of the ecological flow of Qingjiang cascade.

3 Optimal equilibrium operation Model and solution method

3.1 Model establishment

3.1.1 Objective function

(1) Generation scheduling objective function

The traditional cascade medium and long-term optimal dispatching model aims at maximizing the annual

generating capacity and establishes the optimal dispatching model for the cascade hydropower stations. The objective function is as follows:

$$\max E_1 = \sum_{i=1}^n \sum_{t=1}^T P_t^i \cdot \Delta t \quad (1)$$

Where E_1 is total energy production of the cascade within a year; n is the number of reservoirs; T is the total number of steps t in the computational period; P_t^i is power output of i th reservoir at the t th time; Δt is time step.

(2) Objective function of optimal equilibrium operation between power generation and ecology

In order to consider the constraints of ecological flow, the minimum and maximum ecological flow are taken as strong constraints, the flow of suitable upper and lower limits are weak constraint. In order to make the discharge in Qingjiang cascade dispatching process fall between the ecologically suitable upper limit flow and ecologically suitable lower limit flow as far as possible under the condition of satisfying the strong constraint of minimum and maximum ecological flow, the following runoff ecological deviation coefficient is introduced.

$$\gamma_i = 1 - (\omega_1 \frac{1}{T} \sum_{t=1}^T \frac{dQ_{ecoLow,t}^i}{\text{Max}(dQ_{ecoLow,t}^i)} + \omega_2 \frac{1}{T} \sum_{t=1}^T \frac{dQ_{ecoHigh,t}^i}{\text{Max}(dQ_{ecoHigh,t}^i)}) \quad (2)$$

where γ_i is the runoff ecological deviation coefficient of i th reservoir; $\omega_1 = \omega_2 = 0.5$; $dQ_{ecoLow,t}^i$ is the difference between ecological suitable lower flow and reservoir discharge. When the value is negative, the assignment is 0. $dQ_{ecoHigh,t}^i$ is the difference between reservoir discharge and ecological suitable upper flow. When the value is negative, the assignment is 0. We can calculate that γ_i is between $[0, 1]$. $\gamma_i = 0$ represents the worst ecological scheduling, and $\gamma_i = 1$ represents the best ecological scheduling.

The runoff ecological deviation coefficient is added into the target function of the maximum annual power generation, so as to establish the optimal equilibrium operation model between power generation and ecology of Qingjiang cascade hydropower station

$$\max E_2 = \sum_{i=1}^n \gamma_i \cdot \sum_{t=1}^T P_t^i \cdot \Delta t \quad (3)$$

where E_2 is the objective function of optimal equilibrium operation between power generation and ecology

3.1.2 Constraints

(1) Reservoir water balance constraint

$$Q_t^i = (V_{t-1}^i - V_t^i) / \Delta t + I_t^i + q_t^{i-1} - S_t^i \quad (4)$$

(2) Water level limit

$$Z_{t,\min}^i \leq Z_t^i \leq Z_{t,\max}^i \quad (5)$$

(3) Reservoir discharge limit

$$q_{t,\min}^i \leq q_t^i \leq q_{t,\max}^i \quad (6)$$

(4) Power output limit

$$P_{t,\min}^i \leq P_t^i \leq P_{t,\max}^i \quad (7)$$

(5) Guaranteed power output constraint

$$P_t^i = \begin{cases} P_{rt}^i & \text{if } P_{rt}^i \geq P_{bt}^i \\ P_{rt}^i + \beta \cdot (P_{rt}^i - P_{bt}^i) & \text{if } P_{rt}^i < P_{bt}^i \end{cases} \quad (8)$$

where Q_t^i is generation reference flow of i th reservoir at the t th time; V_{t-1}^i is the final storage of the i th reservoir at the $t-1$ th time; I_t^i is the stream flow of intermediate catchment between the $i-1$ th reservoir and the i th reservoir at the t th time; q_t^{i-1} is the water release of the $i-1$ th reservoir at the t th time; S_t^i is the water release through spillway of the i th reservoir at the t th time; $Z_{t,\min}^i$ is the minimum water level of the i th reservoir at the t th time; $Z_{t,\max}^i$ is the maximum water level of the i th reservoir at the t th time; Z_t^i is the water level of the i th reservoir at the t th time; As shown in Figure 1, $q_{t,\min}^i$ is the minimum ecological flow of the i th reservoir at the t th time, $q_{t,\max}^i$ is the maximum ecological flow of the i th reservoir at the t th time; $P_{t,\min}^i$ is the minimum power output of the i th reservoir at the t th time; $P_{t,\max}^i$ is the maximum power output of the i th reservoir at the t th time; P_{rt}^i is the actual power output of the i th reservoir at the t th time; P_{bt}^i is the guaranteed power output of the i th reservoir at the t th time; β is the punish coefficient; P_t^i is the punishment power output of the i th reservoir at the t th time.

3.2 PSO based solution method

Particle swarm optimization (PSO) algorithm is a new type of optimization algorithm based on cluster intelligence. It has the characteristics of simplicity, less dependence on parameters and fast convergence speed. It has been widely used in cascade hydropower stations.

The core operation formulas of particle swarm optimization (PSO) applied to Cascade Hydropower Station Dispatching include^[8]:

$$V_{i,t}^k = \omega \cdot V_{i,t}^{k-1} + c_1 \cdot R_1 \cdot (pbest_i - Z_{i,t}^{k-1}) + c_2 \cdot R_2 \cdot (gbest - Z_{i,t}^{k-1}) \quad (9)$$

$$Z_{i,t}^k = Z_{i,t}^{k-1} + v_{i,t}^k \quad (10)$$

where $V_{i,t}^k$ is the velocity of particle i after the k th iteration at the t th time. ω is momentum coefficient; C_1 and C_2 are constants called acceleration coefficients. Their values are determined by experience, and $C_1 = C_2 = 2$ is usually set. R_1 and R_2 are the two independent random numbers uniformly distributed in the range of $[0, 1]$. $pbest_i$ is the individual optimal solution (individual extreme value) of particle i , $gbest$ is the global optimal solution (global extreme value) currently found for the entire population, and $Z_{i,t}^k$ is the water level of the particle i after the k th iteration at the t th time.

The particle swarm optimization (PSO) algorithm for Qingjiang cascade optimal scheduling is designed as follows^[9]:

1. Setting algorithm parameters.

PSO algorithm parameters such as particle swarm size, maximum iteration number, acceleration coefficients C_1 , C_2 and momentum coefficient ω , particle swarm velocity range $[-V_{max}, V_{max}]$ are determined. The range of particle swarm velocity variation is related to the depth of subsidence of the cascade hydropower stations. Due to the dead water level (350m) of SBY is 50 m away from the normal water level (400m), the GHY is 40 m away from the dead water level (160m) to the normal water level (200m), while the GBZ is only 2 m away from the dead water level (78m) to the normal water level (80m), it is necessary to set the range of particle swarm velocity for each of the three hydropower stations. In this paper, the velocity range of the three hydropower stations is set up from upstream to downstream as $[-5, 5]$, $[-4, 4]$ and $[-0.5, 0.5]$.

2. Generating initial particle swarm

In order to shorten the optimization time of the algorithm, initialization particles are randomly generated within the constraints. For the realization of water balance constraints, the increment of the reservoir can be calculated from the inflow of each dimension (i.e. every ten days). The maximum water level reached when the discharge is equal to the minimum ecological discharge is compared with the normal storage water level (flood control limit water level), and the lower water level is taken as the upper limit of each dimension. The minimum water level reached when the discharge is equal to the maximum ecological discharge is compared with the dead water level, and the larger water level is taken as the upper limit of each dimension. The initial water level is not specified at the initial initialization stage, and a series of initial solutions are formed. In the process of optimization cycle, the water level at the end of the specified period is set, and the solutions which do not satisfy the conditions are gradually eliminated by water balance constraints.

3. Position and velocity update

The particle position and velocity are updated iteratively by using the kernel operation formula (8) and formula (9) of particle swarm optimization (PSO). In the first iteration of the initial particle, the individual optimum is itself, and then the optimal solution is determined by continuous optimization. In the iteration process, if the calculated speed exceeds the speed range, it is set as the corresponding boundary value.

4. Terminate conditions

The fitness objective function which does not satisfy the constraint condition of water balance is zero. Determine whether the optimal solution has reached the maximum number of iterations, if the conditions are met, then exit, otherwise return to step (3).

4 Establishment of evaluation index system

The dispatching scheme of Qingjiang cascade hydropower station is evaluated from the viewpoint of power generation efficiency. The evaluation indexes of the total

amount of power generation and cascade discarded water are mainly considered. The dispatching scheme is evaluated from the viewpoint of basin ecology, the cascade runoff ecological deviation coefficient, the cascade ecological overflow, the cascade ecological overflow percentage, ecological water shortage, and cascade ecological water shortage percentage are proposed.

1. Cascade runoff ecological deviation coefficient

$$\gamma = \sum_{i=1}^n \lambda_i \cdot \gamma_i \quad (11)$$

where γ is runoff ecological deviation coefficient of cascade hydropower stations; λ_i is weighted values for each cascade hydropower station, $\lambda_i = 1/n$.

2. The cascade ecological overflow and its percentage are used to describe the ecological suitable upper limit flow constraint damage degree of cascade hydropower stations.

$$V_{ecoOver} = \sum_{i=1}^n \sum_{t=1}^T dQ_{ecoHigh,t}^i \cdot \Delta t \quad (12)$$

$$\delta_{ecoOver} = \sum_{i=1}^n \lambda_i \frac{\sum_{t=1}^T dQ_{ecoHigh,t}^i \cdot \Delta t}{\sum_{t=1}^T Q_{ecoHigh,t}^i \cdot \Delta t} \times 100\% \quad (13)$$

where $V_{ecoOver}$ is cascade ecological overflow; $\delta_{ecoOver}$ cascade is ecological overflow percentage; $Q_{ecoHigh,t}^i$ is ecological suitable upper limit flow of i th reservoir at the t th time.

3. The Cascade ecological water shortage and its percentage are used to mainly describes the ecological suitable lower limit flow constraint damage degree of cascade hydropower stations.

$$V_{ecoLack} = \sum_{i=1}^n \sum_{t=1}^T dQ_{ecoLow,t}^i \cdot \Delta t \quad (14)$$

$$\delta_{ecoLack} = \sum_{i=1}^n \lambda_i \frac{\sum_{t=1}^T dQ_{ecoLow,t}^i \cdot \Delta t}{\sum_{t=1}^T Q_{ecoLow,t}^i \cdot \Delta t} \times 100\% \quad (15)$$

where $V_{ecoLack}$ is cascade ecological water shortage; $\delta_{ecoLack}$ is cascade ecological water shortage percentage; $Q_{ecoLow,t}^i$ is ecological suitable lower limit flow of i th reservoir at the t th time.

5 Results and discussions

The SBY, the last hydropower station built in Qingjiang River, was put into operation at 2008. Ten-day runoff data of Qingjiang cascade from 2008 to 2010 were selected for cascade optimal operation calculation. The starting and ending water levels for each year of the three hydropower stations are set according to the actual operation of the cascade hydropower stations at the beginning and end of the year^[10]. Specific water level information are shown in Table 1.

Table 1. Qingjiang cascade start and stop water level

Unit: mYear	Unit:m					
	SBY water level		GHY water level		GBZ water level	
	Start	End	Start	End	Start	End
2008	383.73	395.05	196.46	197.44	79.22	79.38
2009	395.05	382.88	197.44	186.15	79.38	79.06
2010	382.88	385.44	186.15	198.00	79.06	79.33

Particle swarm optimization (PSO) algorithm is used to calculate the optimal dispatching model with the objective of maximizing the cascade generation capacity (scheme 1) and the objective of optimal equilibrium operation between power generation and ecology (scheme 2). The dispatching results under the two schemes are shown in table 2. Comparing the dispatching results of the two schemes in Table 2, it can be seen that the total amount of cascade power generation in Scheme 2 is reduced by 1.83% and the amount surplus water is increased by 641 million m³ compared with that in Scheme 1. However, for the optimal equilibrium operation between power

generation and ecology, the increased waste water greatly improves the ecological environment of Qingjiang cascade discharge, and the cascade ecological deviation coefficient of runoff is increased by 6.90%, the cascade ecological overflow decreased by 7.739 billion m³, the cascade ecological overflow percentage decreased by 1.96 percentage points, the cascade ecological water shortage decreased by 130 million m³, and the ecological water shortage percentage decreased by 1.01 percentage points. At the same time, the calculation results show that the cascade ecological overflow of Qingjiang River is much higher than the ecological water shortage.

Table 2. Evaluation results of Qingjiang cascade hydropower stations under two schemes

	Scheme 1				Scheme 2			
	SBY	GHY	GBZ	QJ	SBY	GHY	GBZ	QJ
Power generation 10 ⁸ kwh	37.17	32.17	11.52	80.86	36.45	31.73	11.2	79.38
Surplus water (10 ⁸ m ³)	0	0	4.05	4.05	1.4	1.28	7.78	10.46
Runoff ecological deviation coefficient	0.88	0.88	0.86	0.87	0.95	0.94	0.92	0.93
Ecological overflow (10 ⁸ m ³)	124.13	291.4	458.3	873.84	96.14	265	435.31	796.5
Ecological overflow percentage (%)	11.51	20.35	29.09	20.32	8.92	18.5	27.63	18.35
Ecological water shortage (10 ⁸ m ³)	1.89	1.51	0.93	4.33	1.05	1.29	0.69	3.03
Ecological water shortage percentage (%)	4.84	2.92	1.62	3.13	2.69	2.48	1.2	2.12

Further, taking the dispatch in 2008 as an example for specific analysis, Figure 2 shows the water level, output and flow of the two dispatch schemes. In the scheme 2, the water level of SBY is lower than that of the scheme 1 from 9th to 12th ten days, and the discharge is larger than that of the scheme 1 on the whole, which avoids ecological water shortage in the 15th ten days and ecological overflow in the 16th, 17th, 21th, 22th, 23th ten days. In scheme 2, the water level of GHY is lower than that of scheme 1 in 1th to 4th ten days, higher than that of scheme 1 in 5th to 8th ten days and lower than that of scheme 1 in 9th, 10th ten days, thus avoiding two large ecological overflow in 7th and 11th ten days. In the scheme 1, the water level of GBZ changed greatly three times, while in the scheme 2, the water level changed greatly only once. Figure 2 (b) (d) (f) shows that the discharge of scheme 2 is better between the suitable lower limit flow and the suitable upper limit flow than that of scheme 1. In scheme 1, the discharge of SBY in 12th, 15th ten days and GHY in 10th ten days is lower than the ecologically suitable lower limit flow. In scheme 2, the discharge of each hydropower station is higher than the ecologically suitable lower limit flow, which reduces the ecological water shortage. In scheme 1, SBY in 21th, 22th, 23th, 25th, 30th and 31th ten days, GHY in 7th, 10th, 22th, 30th and 31th ten days, GBZ in 7th, 10th, 22th, 30th and 31th ten days, the discharge significantly exceeded the ecological suitable upper limit flow, but scheme 2 basically

guarantees that when the ecologically suitable upper limit discharge is large, the discharge is also very large. At the same time, the discharge meets the ecologically suitable upper limit flow constraint conditions as far as possible, effectively reducing the ecological overflow.

6 Conclusion

Aiming at the Qingjiang cascade ecological dispatching problem, the optimal equilibrium operation between power generation and ecology are studied in this paper. Firstly, the ten-day frequency method was used to calculate the minimum ecological flow, the maximum ecological flow, the suitable upper and the lower limits of ecological flow. Then, on the basis of the traditional cascade generation optimal dispatching model, the ecological deviation coefficient of runoff is introduced, and the optimal equilibrium operation model is proposed. And power generation and ecological evaluation index system of the dispatching scheme is constructed. Comparing with the traditional power generation optimal dispatch, the example calculation shows that the optimal equilibrium operation model can achieve greater ecological benefits with little loss of power generation benefits, meet the ecological suitable flow requirements to the greatest extent, and effectively improve the Qingjiang cascade flow environment.

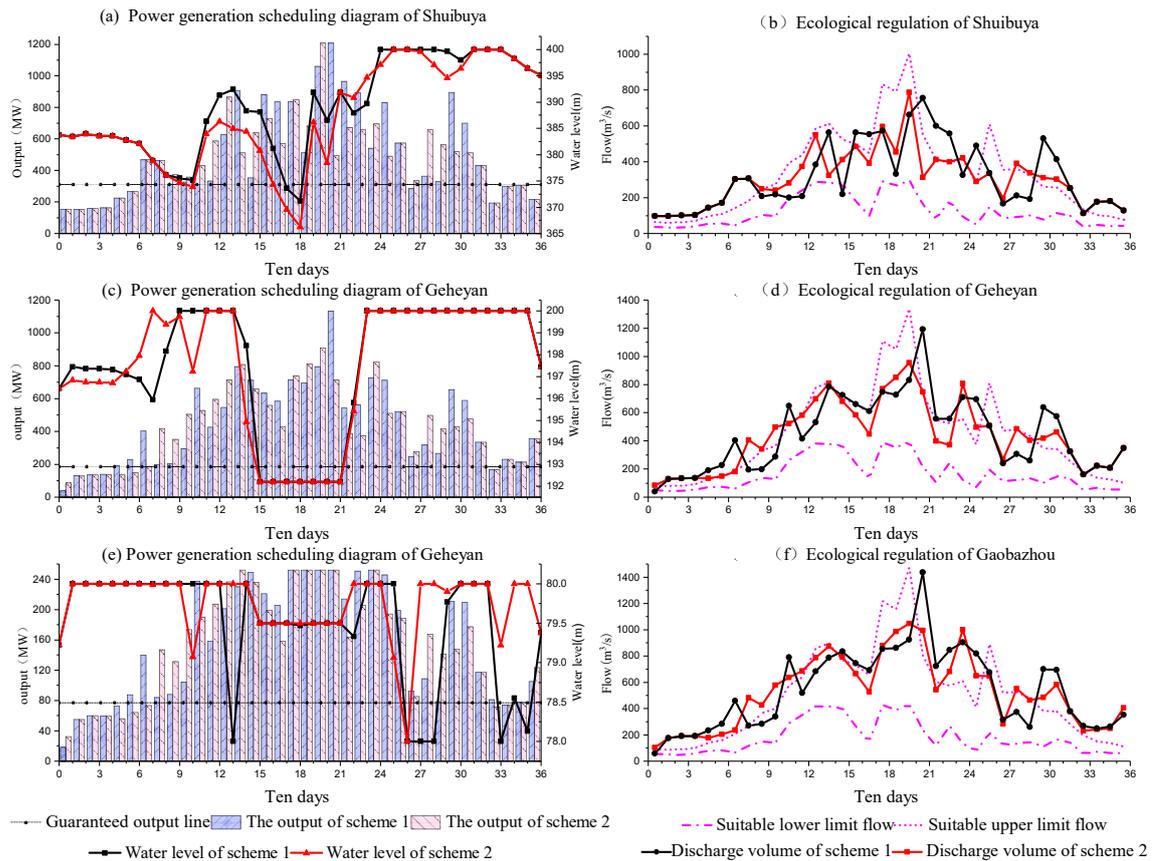


Fig. 3. Results of Qingjiang cascade optimal operation in 2008.

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