Multi-objective ecological operation of cascade reservoirs based on MGCL-PSO algorithm

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Abstract. The reasonable utilization of river water resources requires the joint operation of cascade reservoirs. Aiming at power generation and ecological environment protection, taking the Qingjiang cascade reservoir group as the research object, a multi-objective optimization model for maximum power generation considering ecological base flow and minimum ecological flow changed is established. The results of the multi group cooperation operation particle swarm optimization (MGCL-PSO) model based on population cooperation show that the multi-objective of power generation and ecology can achieve a better balance by slightly reducing the power generation. Several schemes with good convergence are obtained from the calculation results, which provide a reference for the operation of cascade reservoirs.

Keywords: cascade reservoir group; ecological operation, MGCL-PSO algorithm; multi-objective optimization

1. Introduction
Since the middle of the 20th century, with the continuous development of industrial development and people's demand for electricity in production and life, a large number of hydropower stations have been built around China, which has made great contributions to China's modernization. However, the traditional hydropower dispatch often ignores the needs of the ecological environment, and more often seeks to maximize economic benefits for dispatch. This has also led to changes in the morphological structure of the river channel, a decrease in the diversity of the channel system shape, and a decrease in the heterogeneity of the ecological environment. A series of river ecological problems, such as reduced biodiversity and reduced self-purification capacity of water bodies.

Reservoir ecological dispatching is a measure to reduce the negative impact of dam construction and operation on river ecosystems. The relatively low cost of this measure can help improve traditional reservoir dispatching methods, rationally operate dam facilities, partially restore natural hydrological conditions, and restore the ecosystem structure and function of rivers upstream and downstream of the dam. Under the premise of ensuring that the ecological environment will not be damaged or even restore the already damaged river ecological environment, improving the economic benefits of hydropower stations is the purpose of ecological dispatch research.

With the development of hydropower resources, more than one reservoir is often built on a river, and the ecological demand of the river is not only satisfied by the operation of one reservoir, so it needs the joint operation of cascade reservoirs with hydraulic connection to meet the ecological environment demand of the river.
In recent years, the problem of ecological regulation has been a research hotspot for researchers. Many scholars have applied ecological dispatching to hydropower dispatching. Li et al have studied the Xiluodu-Xianjiaba Cascade Reservoir joint optimization scheduling that takes into account the downstream ecological flow [1]. Wang et al has studied the effect of ecological dispatch of cascade hydropower hubs on the waterway of the reservoir area, and it was found that the first ecological dispatch of the Hanjiang cascade reservoir caused the channel conditions of the reservoir area to change[2]. The ecological friendly model proposed by Huang et al verified the effectiveness of the system coordination and significantly reduced the water shortage ratio[3]. Yang et al research shows that the joint operation of the Three Gorges reservoir group can help to control the ecological environment[4]. Scholars have incorporated ecological dispatch into the research of reservoir dispatch, and they have required multiple objectives for reservoir dispatch.

Maintaining a reasonable ecological runoff is the basic requirement for reservoir ecological regulation. So far, there are more than 200 methods for calculating the ecological baseflow of rivers, which can be roughly divided into 4 categories: hydrological methods (7Q10 method, Tennant method), hydraulic methods (R2CROSS method, wet cycle method), ecological flow analysis method (RCHARC method, Basque method) and ecological environment simulation method (IFIM method, CASIMIR method)[5], among which the hydrological method is most suitable for most rivers in China it is Tennant law.

Particle Swarm Optimization (PSO) is a swarm intelligence algorithm proposed by Kennedy and Eberhart in 1995 [6]. The PSO algorithm has fast convergence speed and strong optimization ability, but there are also problems such as particle convergence in later stages. This paper improves the PSO algorithm, and proposes a multi-group cooperative particle swarm algorithm (MGCL-PSO), which introduces multiple particle populations and optimizes their cooperation. While increasing the global search capability, it avoids particle convergence and misses the most excellent solution. The core idea is to use the cooperation between populations with different particle velocities and the sharing of historical global optimal positions, combining the global search capability of the PSO algorithm with the local search capability, so as to maintain the fast convergence speed and take into account the global search ability. Greatly improved the algorithm's ability to find the optimal solution.

In this paper, the first section is a brief introduction. In the second section, the medium and long-term optimization model is established to achieve the goal of maximum power generation and optimal ecological flow. The third section uses the improved Tennant method to determine the optimal ecological flow. In the fourth section, MGCL-PSO algorithm is proposed to solve the shortcomings of the original PSO algorithm. In the fifth section, taking the Qingjiang cascade reservoir group as an example, using the established model and MGCL-PSO algorithm, several scheduling schemes are obtained, and the relationship between multiple objectives is analyzed. In the sixth section, the conclusion is drawn. Finally, in the seventh section, this paper summarizes.

2. Establish a dispatching model for maximum generation and ecological benefits of cascade reservoirs

This paper establishes the maximum power generation model and the best ecological outflow model. The scheduling period is divided into T periods, and the objective function is to maximize the power generation and ecological benefits of the cascade reservoirs in the basin. Establish a scheduling model, and set the water level, discharge flow, storage capacity, output, and water balance as constraints. The details are as follows[7] [8].

2.1. Objective function
The aims of the model are to achieve maximum power generation and optimal ecological benefits of the power station. The functions of the two objectives are as follows:

1) Maximum power generation
\[ F_i = \max \sum \sum K_i Q_i H_i \Delta t \]  

(1)

Where \( n \) is the number of cascade reservoirs, \( i \) is the reservoir serial number, \( i \in [1,n] \); \( T \) is the total number of time periods, \( t \) is the time series number, \( t \in [1,T] \) ; \( Q_i, H_i \) are the Power generation flow, head, generation time and comprehensive output coefficient of the \( i \)-th cascade reservoir in the \( t \)-th period.

(2) Best ecological outflow

In order to maintain the ecological environment, according to the relationship between the flow size and the ecological environment, the researchers determined the ecological quality level of the flow. The gap between the supply of ecological water and the optimal ecological flow should be the smallest [9].

\[ F_2 = \min \sum \sum \frac{1}{T} (R_{st} - Q_{st}) \]  

(2)

Where \( n \) is the number of cascade reservoirs, \( i \) is the reservoir serial number, \( i \in [1,n] \); \( T \) is the total number of time periods, \( t \) is the time series number, \( t \in [1,T] \) . \( R_{st} \) and \( Q_{st} \) are the reservoir discharge and ecological water demand respectively of the \( i \)-th cascade reservoir in the \( t \)-th period.

2.2. Constraints

This model has 5 constraint conditions:

(1) Output restraint

\[ N_{it,min} < N_{it} < N_{it,max} \]  

(3)

Where \( N_{it,min} \) and \( N_{it,max} \) are the minimum output and maximum output of the \( i \)-th cascade reservoir in the \( t \)-th period.

(2) Reservoir capacity constraints

\[ V_{it,min} \leq V_{it} \leq V_{it,max} \]  

(4)

Where \( V_{it,min} \) and \( V_{it,max} \) are the minimum and maximum storage capacity of the \( i \)-th cascade reservoir in the \( t \)-th period.

(3) Outflow constraint

\[ R_{it,min} < R_{it} < R_{it,max} \]  

(5)

Where \( R_{it,min} \) and \( R_{it,max} \) are the minimum and maximum outflow of the \( i \)-th cascade reservoir in the \( t \)-th period.

(4) Water level constraint

\[ Z_{it,min} < Z_{it} < Z_{it,max} \]  

(6)

Where \( Z_{it,min} \) and \( Z_{it,max} \) are the minimum and maximum water level of the \( i \)-th cascade reservoir in the \( t \)-th period.

(5) Water balance of cascade reservoirs

\[ V_{it} = V_{i,t-1} + (q_{it} - (R_{it} - R_{i-1, it}) \Delta t \]  

(7)

Where \( V_{it} \), \( q_{it} \), \( R_{it} \) are the storage capacity, inflow, and outflow of the \( i \)-th cascade reservoir in the \( t \)-th period. \( R_{i-1, it} \) is the outflow of the \( i-1 \)-th cascade reservoir in the \( t \)-th period.

3. Improved Tennant method

Tennant method, also called the Montana method, is one of the calculation methods of ecological base flow in the river control section. In the Tennant method, based on a predetermined multi-year average
flow percentage, the recommended river flow values for protecting the water ecological river environment are divided into the maximum allowable limit value, the optimal range value, the excellent state value, the very good state value, 1 high limit standard, 1 best range standard and 6 low limit standards, such as good state value, general or poor state value, poor or minimum state value, and extreme state value, according to the seasonality of aquatic organisms to the environment. The requirements are different, divided into the spawning and fattening period of fish from April to September and the general water period from October to March of the following year.

Rivers that are generally affected by farmland irrigation, water resources scheduling, and other human influences have hydrological processes that are discontinuously alternating within and between years. The average flow over many years is often affected by the maximum flow during the wet season or the minimum flow during the dry season. The oscillating changes have weakened the peak and valley values of intra-annual and inter-annual flow, and the flow process of the river has been flattened. The Tennant method does not exclude the interference of these extremely discrete data, but directly adopts a certain proportion of the average flow for many years as the ecological base flow. To avoid the impact of extreme events caused by human activities on the possible deviation of the ecological base flow calculation, it is necessary to consider the interrelationship between the overall inter-annual runoff law and the annual runoff law in each year, improve the Tennant method, and select a representative one. The proportion of the typical annual flow that can reflect the ecological environment of the river is used as the basis for the calculation of the average flow for many years, and the flow process line is modified to make it more in line with the actual situation [10].

This paper will select 30% and 20% of the average flow for many years as the minimum ecological flow in flood season and non-flood season, respectively. 60% and 100% of the multi-year average flow are selected as the upper and lower limits of the optimal ecological flow, respectively. Instead of choosing a fixed value as the optimal ecological flow, a range is selected.

4. MGCL-PSO algorithm

Particle swarm optimization (PSO) is a global evolutionary optimization algorithm based on swarm intelligence, which simulates the foraging behavior of birds. Individuals of the population cooperate to find the optimal solution. The potential solution of each optimization problem is a particle in the search space. Each particle has two characteristics of position and speed. The target function corresponding to the particle’s position coordinate can be used as the fitness of the particle. The algorithm measures the quality of the particle through the fitness. In each iteration, particles update themselves by tracking two extremums. The first extreme value is the optimal solution found by the particle itself, which is called the individual extreme value Pbest; the other extreme value is the optimal solution found by the whole population at present, which is the global extreme value Gbest.

Standard particle swarm optimization has the advantages of easy operation, fast execution speed and high efficiency. But PSO algorithm also has the characteristics of low precision and easy divergence. If the parameters such as acceleration coefficient and maximum velocity are too large, the particle swarm may miss the optimal solution and the algorithm does not converge. If the parameters such as acceleration coefficient and maximum speed are too small, the convergence of the algorithm will be slow, the local optimization ability will be weak. To solve these problems, Shi et al proposed the inertia weight method, whose particle velocity updating formula is [11]

\[
v_{id}^{k+1} = \omega v_{id}^k + c_1 \times rand_1^k \times (Pbest_{id}^k - x_{id}^k) + c_2 \times rand_2^k \times (Gbest_{id}^k - x_{id}^k)
\]

(8)

In the equation, \(x_{id}^k\) and \(v_{id}^k\) are the current position and velocity of particle \(i\) in the \(d\) dimension of the \(k\)-th iteration, \(c_1\) and \(c_2\) is the learning factor, \(rand_1\) and \(rand_2\) are the random numbers between [0,1]. \(\omega\) is the inertial factor. It can play a certain role by using the linear and fuzzy adjustment methods, but the linear adjustment strategy does not combine the global search and the local search completely. However, the implementation of the fuzzy adjustment strategy is more difficult and cannot be widely used [12].
Therefore, because of the shortcomings of PSO algorithm, this paper introduces multi group cooperation operation into PSO algorithm to form a new multi group cooperation algorithm (MGCL-PSO). Several particle groups are introduced into MGCL-PSO, and the $\omega$ value of each particle group is calculated according to the following formula (9)

$$
\omega_i = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{n} \times i
$$

(9)

where $\omega_i$ is the inertia factor of the $i$-th population, $n$ is the total population, $\omega_{\max}$ and $\omega_{\min}$ are the maximum and minimum values of $\omega$, respectively. According to the size of $\omega$, the global search ability of each population is different, and the population with the smallest $\omega$ has the strongest local search ability.

MGCL-PSO algorithm gradually transfers the global optimal solution from the population with a strong global search ability to the population with strong local search ability. By combining global search and local search in the way of population cooperation, it can not only achieve the characteristics of fast convergence, but also take into account the advantages of high precision.

The algorithm steps are as follows:

1. initializes the population number and the inertia weight $\omega$ of each population.
2. initializes the speed, position and local optimal solution of each particle in each population.
3. calculates the fitness of each particle.
4. get the global optimal solution of each population by comparison.
5. rank the population with $\omega$ value from large to small, start from the population with maximum $\omega$ value and transfer the global optimal solution of its own population to the next population.
6. Sort according to step 5, and the global optimal solution of the previous population is compared with that of its own population. If the global optimal solution of the previous population is better, the position of its solution is given to the particle of the global optimal solution of the population, and the global optimal solution is replaced.
7. rank the population according to the omega value from large to small, repeat step 5 and step 6 until all populations are compared.
8. update the speed, position and local optimal solution of all populations
9. if the termination condition is satisfied, the stop iteration outputs the maximum of the global optimal value of the last iteration, which is the optimal value point and the optimal value; otherwise, the particle recording returns to step 3, and the algorithm continues to operate.

The algorithm flow chart is shown in Figure 1.
5. Study on multi-objective operation of Qingjiang Cascade Reservoirs
5.1. Background of Qingjiang cascade project
In order to reflect the application effect of MGCL-PSO algorithm, Qingjiang Cascade Reservoirs are selected for example calculation. Qingjiang River is the first tributary of the Yangtze River after it leaves the Three Gorges, with a total length of 423 km. Shuibuya hydropower station is the top-level leading project of cascade rolling development in the Qingjiang River Basin, with multi-year regulation capacity. The power generation is the main part of the power station along the river, with annual regulation capacity. Gaobazhou is the reverse regulation power station along the river. The main parameters of each reservoir are shown in Table 1.

Table 1. Main parameters of Qingjiang Cascade Reservoirs.

| Qingjiang Cascade Reservoir Group | Normal water level/m | Flood limit water level/m | Dead water level/m | Total storage capacity / 10^4 m^3 | Installed capacity / MW | Guarantee output / MW | Comprehensive output coefficient |
|----------------------------------|----------------------|--------------------------|-------------------|-------------------------------|-----------------------|-----------------------|-------------------------------|
| Shui Bu Ya                       | 400                  | 391.8                    | 350               | 45.80                         | 1840                  | 312                   | 8.5                           |
| Ge He Yan                        | 200                  | 192.2                    | 161.2             | 34.80                         | 1212                  | 187                   | 8.5                           |
| Gao Ba Zhou                      | 80                   | 79.5                     | 78                | 4.426                         | 252                   | 61.5                  | 8.4                           |

5.2. Dispatching plan
Maximum power generation plan: Aiming at maximum power generation, taking into account the minimum ecological water requirements.

Minimal ecological flow change plan: While meeting conventional constraints such as guaranteed output, the goal is to minimize the ecological flow change.

5.3. Scheduling period and calculation period division
In this paper, selects the inflow data of Qingjiang cascade reservoirs in 2011, the scheduling period is 10 days, 36 scheduling periods in total. The normal pool level will be selected as the water level at the beginning and end of the regulation period. In this paper, Tennant improved method is used to calculate the ecological flow of Qingjiang cascade reservoir group, as shown in Figure 2, 3 and 4. We can see from figures 2 to 4 that as cascade reservoirs connected in series, their inflow and ecological water demand have similar trends. Due to the difference between upstream and downstream, the inflow and ecological water demand are increasing from Shuibuya reservoir (figure 2) to Gaobazhou reservoir (figure 4).

Figure 2. Ecological flow of Shuibuya reservoir.
5.4. Parameter settings

According to the optimization idea and process of MGCL-PSO algorithm, the program is written by java to optimize the design. The number of population is selected as 8, the number of particles in each population is 60, and the maximum number of iterations is 500, $c_1$ is 2, $c_2$ is 2, $\omega_{\text{max}}$ is 0.9, $\omega_{\text{min}}$ is 0.2. The 10 sets of optimal solutions aiming at the maximum power generation and the best ecological outflow are obtained by the MGCL-PSO algorithm.

6. Results

In this paper, the optimal dispatching example is calculated by using the inflow of the Qingjiang cascade reservoir group in 2011. Under the condition of satisfying the power generation benefit and ensuring the minimum output, the ecological water demand of the discharge flow is considered. Table 2 shows the multi-objective optimal operation plan of Qingjiang cascade reservoir group. It can be seen from table 3 that the degree of change in ecological flow is inversely proportional to the amount of electricity generated. Increasing the efficiency of ecological dispatch will inevitably lead to a decrease in power generation. As can be seen from the table as a whole, the MGCL-PSO algorithm is suitable for solving multi-objective optimization model problems.

In order to further analyze the differences between the various scheduling schemes, two schemes were selected for comparison: scheme 1 (maximum power generation) and scheme 11 (minimum ecological flow change). (1) When the multi-objective optimization model takes power generation as the main target, then scheme 1 can be selected; (2) When the multi-objective optimization model is based on the optimal ecological outflow, the scheme 11 can be selected; therefore, the large reservoir

Figure 3. Ecological flow of Geheyan reservoir.

Figure 4. Ecological flow of Gaobazhou reservoir.
can be selected according to the actual situation of the power station. Figures 5 to 7 show the water level change and discharge process of the Qingjiang cascade reservoir group under two typical optimization schemes. We can see the difference between the operation water levels of the two schemes. In multiple periods, the operation water level of the scheme 1 is higher than that of the scheme 11. Figure 8 to 10 show the Power generation outflow. Obviously, the outflow of scheme 11 is more gentle and close to the optimal ecological outflow change and discharge process of the Qingjiang cascade reservoir group under two typical optimization schemes.

For further comparison, we add scheme 10 in the following to quantify the differences between the three schemes. The power generation and ecological flow change of scheme 10 is between scheme 1 and scheme 11.

**Table 2. Operation results.**

| Scheme | Maximum Power Generation (10^8kW·h) | Minimum Ecological Flow Change (%) |
|--------|-------------------------------------|-----------------------------------|
| 1*     | 72.48                               | 0.344                             |
| 2      | 72.46                               | 0.345                             |
| 3      | 72.45                               | 0.341                             |
| 4      | 72.44                               | 0.344                             |
| 5      | 72.43                               | 0.337                             |
| 6      | 72.42                               | 0.332                             |
| 7      | 72.38                               | 0.331                             |
| 8      | 72.35                               | 0.329                             |
| 9      | 72.31                               | 0.328                             |
| 10     | 72.30                               | 0.326                             |

| Scheme | Minimum Power Generation (10^8kW·h) | Ecological Flow Change (%) |
|--------|-------------------------------------|---------------------------|
| 11*    | 71.04                               | 0.197                     |
| 12     | 71.04                               | 0.199                     |
| 13     | 71.06                               | 0.202                     |
| 14     | 71.22                               | 0.204                     |
| 15     | 71.02                               | 0.207                     |
| 16     | 71.03                               | 0.212                     |
| 17     | 71.16                               | 0.218                     |
| 18     | 71.14                               | 0.219                     |
| 19     | 70.98                               | 0.220                     |
| 20     | 70.96                               | 0.223                     |

**Figure 5.** Water level of Shuibuya reservoir.
Figure 6. Water level of Geheyan reservoir.

Figure 7. Water level of Gaobazhou reservoir.

Figure 8. Power generation outflow of Shuibuya reservoir.
Table 3. Comparison of operation results.

| Scheme | Power Generation (10^8kW·h) | Power Generation Decline (%) | Ecological Flow Change (%) | Ecological Flow Change Increase (%) |
|--------|-----------------------------|-------------------------------|---------------------------|-------------------------------------|
| 1      | 72.48                       | -                             | 0.344                     | 74.62                               |
| 10     | 72.3                        | 0.25                          | 0.326                     | 65.48                               |
| 11     | 71.04                       | 1.99                          | 0.197                     | -                                   |

(a) When only the maximum generation is considered, scheme 1 is superior to other schemes. It can be seen from table 3 that scheme 1 also generates 2% more power than option 11.

(b) When only considering the maximum ecological benefit and the minimum change of ecological flow, scheme 11 is superior to other schemes, and it can be seen from table 3 that the change of ecological flow of scheme 1 is 74.62% more than that of scheme 11, and the change of ecological flow of scheme 11 is only about half of that of scheme 1.

(c) The power generation of scheme 10 is smaller than that of scheme 1, and the change of ecological flow is larger than that of scheme 11. However, it can be seen from table 3 that the power generation of scheme 10 is only 0.25% less than that of scheme 1, but the change of ecological flow is 9.14% smaller.
We can see that the difference between the maximum power generation scheme and the optimal ecological outflow scheme is large in the period of less water. The optimal ecological outflow scheme will discharge in the period with less water to ensure the ecological water flow of the river to protect the ecological environment of the river, while the maximum power generation scheme tends to generate electricity with less flow in the period with less water to maintain high water level; this also leads to the operation level of the optimal ecological outflow scheme is lower than the maximum power generation scheme in the flood season.

It can be concluded from the above points that a small reduction in power generation can bring about a great improvement in ecological flow. This provides us with ideas in the multi-objective operation of cascade reservoirs. It is worth using the cost of power generation reduction in exchange for the improvement of ecological flow. It is a strategy that we should consider in the future operation of the cascade reservoir group to obtain the balance among multiple targets at a small cost, so that multiple targets can achieve better results.

To sum up, when the energy efficiency requirements are high and the power generation is required to undertake the main benefit tasks, scheme 1 is recommended; when the protection of the ecological environment is the main criterion, scheme 11 is recommended; when the power generation benefit and ecological protection want to achieve the balance, other schemes can be selected according to the requirements of the two objectives. From the above we prove that it is cost-effective to achieve such a balance.

7. Conclusion

With the deepening of hydropower development in China, the joint operation of cascade reservoirs plays an increasingly important role. At the same time, only the joint operation of cascade reservoirs can meet the ecological water demand of the river where the cascade reservoirs are located. In this paper, a multi-objective optimization model of maximum power generation and optimal ecological outflow is established, and aiming at the problem of local convergence and slow convergence of traditional particle swarm optimization algorithm in the later stage, the original PSO algorithm is modified by introducing the concept of multiple groups, using the way of cooperation between populations with different inertia factors, taking into account the local and global search capabilities of PSO algorithm MgCl-PSO algorithm is proposed. MgCl-PSO algorithm is applied to solve the multi-objective optimization model of Qingjiang cascade reservoirs. For this high-dimensional problem with high complexity, MgCl-PSO algorithm effectively overcomes the shortcomings of the original PSO algorithm, and obtains many satisfactory results in effect and rationality.

The analysis shows that reducing the total power generation of the cascade reservoirs can greatly improve the ecological effect of the rivers where the cascade reservoirs are located, which is of great significance to solve the imbalance between the ecological environment protection and economic development needs of the rivers with multiple reservoirs. The research in this field should be strengthened in the future work.

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