A Research on Multi-objective Generation Optimization Scheduling of the TGC Reservoirs Considering Ecological and Shipping Benefits

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Abstract. Due to the increasing energy demand and the lack of comprehensive utilization of water resources, this paper has established a generation-shipping-ecological optimization (GSEO) model to balance the benefits between shipping, power generation and ecology. Then, the Three Gorges Cascade (TGC) is taken as the research object, and the efficiency evaluation methods of shipping and ecological benefits are proposed. Finally, the actual inflows of the abundant, average and dry years are studied as the samples to solve the GSEO model. The simulation results indicate that the model and the benefit evaluation methods proposed in this paper are feasible and effective.

1. Introduction
Along with China population growth and rapid economic development, energy demand is increasing at the same time. As a pure and clean energy, hydropower has the advantages of renewable, pollution-free, low operating cost and easy for peak load regulation, which is widely favored by all countries in the world. The hydropower station is also carrying out other comprehensive benefits while generating electrical energy. How to consider multiple benefits in reservoir scheduling and improve the operation level of reservoir is the target of this paper. For this purpose, this paper will take the Three Gorges Cascade (TGC) in China as the research object, consider other benefits in the generation scheduling, and realize the efficient utilization of water resources.

As the "golden waterway" of China, the Yangtze River runs through China's eastern and western regions, and its great capacity is irreplaceable by other means of transportation. As a control center of the middle and lower reaches of the Yangtze River, the TGC has an important strategic position for the regulation of navigation in the middle and lower reaches. Therefore, it is necessary to study the shipping schedule of the TGC. The operation of the TGC will inevitably pose a threat to the ecosystem of the river basin, therefore, how to effectively reduce the adverse effects on the ecological habitat of the basins while making full use of the large-scale cascade, is also the difficult problem to be solved. This paper will take the TGC in China as the research object, consider the ecological and shipping benefits in the generation scheduling, and realize the efficient utilization of water resources.

At present, there are few researches on multi-objective scheduling of shipping. In terms of ecological benefit evaluation, the commonly used methods are IFIM[1] method, RVA[2] method,
Tennant[3] method and so on. In terms of power generation, Kumar[4], Wu[5] and Hui[6] have in-depth research, and the simulation results are good. The multi-objective optimization algorithm has been widely used in the reservoir dispatching[7][8], and the algorithm is rich in variety and improvement. On the basis of existing research and the current situation of the TGC dispatching, this paper proposes the method of considering the shipping benefit in the reservoir dispatching by simulating the operation process of the actual ship lock. Then, an ecological benefits calculation method is introduced to establish a multi-objective generation scheduling model considering ecological and shipping objectives. A multi-objective optimization algorithm is used to solve the model, and finally the TGC operation schemes with generation, shipping and ecological benefits are given.

2. Multi-objective power generation optimization model

The contradictions between the three benefits of shipping, power generation and ecology are obvious during the Storage period. Therefore, the paper has established a generation-shipping-ecological optimization (GSEO) model.

2.1. Objective function

In this paper, the GSEO model includes three scheduling objectives of generation, shipping and ecology, and the mathematical expression of the objective function is shown below

(1) Shipping benefit: the total accumulative retention weight of goods (TAG) in the waterway is the evaluation standard for shipping

\[ \min f_1 = \min \sum_{t=0}^{T} PL(D_t, Q_t) \]

(2) Generation benefit: the total power generation of cascade power station

\[ \max f_2 = \max \sum_{i=1}^{Num} \sum_{t=1}^{T} K_i Q'_i H'_i \Delta t = \max \sum_{i=1}^{Num} \sum_{t=1}^{T} N_i \Delta t \]

(3) The ecological benefits are evaluated by the average habitat area (See section 4 for details of WUA method) of the Chinese sturgeon

\[ \max f_3 = \max \frac{1}{T} \sum_{t=0}^{T} WUA(Q_t) \]

where \( PL(D_t, Q_t) \) is the TAG in \( t \)th period, \( Num \) is the number of the power stations in the cascade, \( T \) is the total number of the periods, \( K_i \) is the output coefficient of the \( i \)th power station, \( Q'_i \) \( H'_i \) \( \Delta t \) and \( N_i \) are the generation flow, average water head and average output respectively, \( \Delta t \) is the time length of a period, \( WUA(Q) \) is the average habitat area calculated by the WUA method.

2.2. Model constraints

In order to ensure the safe and stable operation of the cascade power station, the relevant dispatching rules of cascade hydropower stations are referenced. The dispatch constraints of the cascade hydropower stations mainly includes water level constraints, water balance constraints, power output constraints and discharged flow constraints.

(1) Water level constraints

\[ Z_{i,t}^{\min} \leq Z_{i,t} \leq Z_{i,t}^{\max} \]

where \( Z_{i,t} \) is the water level of the \( i \)-th power station at the \( t \)-th period; \( Z_{i,t}^{\min} \) and \( Z_{i,t}^{\max} \) respectively stand for the upper limit and lower limit of water level.

(2) Power output constraints

\[ N_{i,t}^{\min} \leq N_{i,t} \leq N_{i,t}^{\max} \]
where \( N_{i,t} \) is the power output of the \( i \)-th power station during the \( t \)-th period; \( N_{i,t}^{\text{min}} \) and \( N_{i,t}^{\text{max}} \) respectively stand for the upper limit and lower limit of power output.

(3) Flow constraint

\[
Q_{i,t}^{\text{min}} \leq Q_{i,t}^X \leq Q_{i,t}^{\text{max}}
\]

where \( Q_{i,t}^{\text{min}} \) is the discharge of the \( i \)-th power station during the \( t \)-th period; \( Q_{i,t}^{\text{min}} \) and \( Q_{i,t}^{\text{max}} \) respectively stand for the upper limit and lower limit of outflow.

(4) Water balance constraints

\[
V_{i,t+1} = V_{i,t} + (I_{i,t} - Q_{i,t}^X) \times \Delta t
\]

\[
I_{i,t} = Q_{i,t}^X + q_t
\]

where \( V_{i,t} \) is the capacity of the \( i \)-th power station of the \( t \)-th period; \( I_{i,t} \) is the inflow of the \( i \)-th power station; \( \tau \) is the flow time; \( I_{i,t} \) is the inflow of the power station in the lower reaches; \( Q_{i,t}^X \) is the discharge flow of the power station in the upper reaches of the \( (t-\tau) \)-th period; \( q_t \) is the inflow of the river between these two power stations.

(5) Limitation of shipping capacity

\[
D'_t \leq D_t^{\text{max}}
\]

Where \( D'_t \) is the amount of goods through the lock in the \( t \)-th period; \( D_t^{\text{max}} \) is the capacity of shipping in the \( t \)-th period.

### 3. Shipping benefit evaluation

In this paper, the research object is the TGC, so when discussing the shipping benefit, the default object is the TGC.

The TGC is a comprehensive hydro project built on the main stream of the Yangtze river, its main tasks are flood control, power generation and shipping. The TGC is composed of the Three Gorges Dam and the Gezhouba Dam, the Gezhouba Dam is 38km downstream. The TGC has a double-line ship lock. The construction of the ship lock was started on April 17, 1994, and on June 16, 2003, it entered the commissioning phase and passed the acceptance inspection on July 8, 2004. As at December 25, 2013, the ship lock had operated 94558 times, passed 59.30 million vessels and 645 million tons of goods, undertook a important transport mission.

For the TGC, The most influential factor for shipping is the discharge flow of the Three Gorges Dam, and the can also directly reflect the operation effect of the dispatch. Therefore, the discharge flow process is used to analyse the shipping benefits.

![Figure 1. Schematic diagram of navigation structure of the TGC](image)

The navigation structure of the TGC is shown in figure 1. The navigation ability is up to the water flow of the interval channel, which is determined by the discharge flow of the Three Gorges Dam. Ships of different tonnage follow different rules, which are show in Table 1.
Table 1 The navigation limit flows of the interval channel (m$^3$/s)

| Ship power (Tons) | the highest discharge going up | the highest discharge going down |
|-------------------|--------------------------------|---------------------------------|
| > 4000            | 45000                          | 45000                           |
| 3001 to 4000      | 40000                          | 45000                           |
| 2001 to 3000      | 35000                          | 40000                           |
| 1001 to 2000      | 30000                          | 35000                           |
| 501 to 1000       | 25000                          | 30000                           |
| < 500             | 25000                          | 25000                           |

The way to calculate the TAG is shown in Fig.2.

The WUA evaluation curve used in this paper is from the literature[10], the relationship between the discharge flow of the TGC and the suitable habitat area of the Chinese sturgeon is shown in Fig.3.

4. Ecological benefit evaluation
This paper introduces the WUA[9] method to evaluate the ecological benefit. WUA is a biological physical habitat simulation method, this paper uses this method to evaluate the suitability of target species habitat under different water flows. The Chinese sturgeon is a rare species living in the downstream channel of the TGC, and The research results of its habitat and breeding conditions are abundant. Therefore, this paper chooses Chinese sturgeon as the target species of ecological evaluation. The WUA evaluation curve used in this paper is from the literature[10], the relationship between the discharge flow of the TGC and the suitable habitat area of the Chinese sturgeon is shown in Fig.3.

Figure 2. Schematic diagram of TAG calculation

Figure 3. The WUA evaluation curve of the Chinese sturgeon
5. Case study
In this paper, a multi-objective optimization algorithm is introduced, and the above shipping and ecological evaluation methods are applied to study the GSEO model.

5.1. Optimization algorithm
This paper uses a kind of modified multi-objective differential evolution algorithm (MODE) [11] to solve the GSEO model proposed. The flow chart of the algorithm is shown in Fig.4.

5.2. Simulation results and analysis
The start time of the water storage schedule is September 10, which lasts for 80 days. The abundant year is 1907, the average year is 2014, the dry year is 2006. So the inflows of the year 2006, 2014 and 1907 are as the study cases, and the simulation results are shown in fig.5, 6 and 7.

Figure 4. Flow chart of multi-objective difference algorithm [11]

Figure 5. Optimization scheduling solution set of year 2006
As can be seen from the fig.5, the TAGs of all the schemes in the solution set of year 2006 are 0, this is due to the small amount of water in the storage period of the year 2006. In order to achieve the purpose of full impoundment, the discharge flow should be small, so that the flow of the interval channel has no impact on shipping. At the same time, it can be seen that there is an obvious antagonistic relationship between the generation and the ecological benefit without considering the shipping. From fig.6 and 7, it can be seen that the smaller the water inflow is, the more obvious the antagonistic relationship between power generation and ecology benefits are, so a greater ecological benefit would require more water consumption, which would lead to reduction of the power generation. Because the inflow in early storage period is still large, the operation mode is similar to that of the flood period, so as to improve the shipping benefit by decreasing the discharge during the period with small water inflow. However, in the later period of the storage period, the water inflow decreases, and the discharge flow has no longer impeded the shipping benefits.

6. Conclusions
This paper takes the TGC as the research object, through the analysis of actual operation data, the flow in the interval channel is taken as the reflection of shipping benefit, which can be calculated based on the actual ship lock operation. WUA method was introduced to evaluate the ecological benefits of the Chinese sturgeon habitat in the lower reaches of the TGC. Then, a kind of modified multi-objective differential evolution algorithm is applied to solve the GSEO model. Finally, the actual inflows of the three years are studied. It can be concluded that the GSEO model and the shipping and ecological evaluation methods proposed in this paper are feasible and effective.

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