

# Multi-objective Dispatching Benefit Evaluation System for Cascade Hydropower Stations

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**Abstract.** In order to master the dispatching level of cascade hydropower stations and guide them to know how to operate in the future, based on the analysis of the factors affecting the dispatching results, a multi-objective evaluation system of power generation, flood regulation, ecology and water supply, which combines qualitative analysis with quantitative analysis, is constructed in this paper. The AHP method is used to solve the problem of determining the weights among the factors and the evaluation criteria. The quasi part adopts the idea of frequency division calculation to divide the evaluation grade scale. The final evaluation index system is more comprehensive and representative, the evaluation process is intuitive and easy to operate, easy to put into practical application

## 1 Introduction

Under the background of energy development pursuing “clean, low-carbon, safe and efficient” and hydropower vigorous development, the joint operation and scheduling of cascade reservoirs is prevailing. This model is conducive to mutual compensation (water quantity, hydraulic power) to improve the comprehensive utilization efficiency and break the limitation of single station operation., ease the pressure of flood control and improve the competitiveness of enterprises. In order to understand the current level of dispatching operation of cascade reservoirs and to guide the management ideas of hydropower stations, a complete indicator system is needed to evaluate them. However, for the cascade reservoir group, although the current assessment method can reflect the scheduling level of the reservoir group to a certain extent, its assessment ideas are inconsistent with the development trend of the hydropower station optimization dispatch [1], the empirical parameters and empirical formulas used in the assessment calculation. There are actual deviations, and the assessment object does not reflect the concept of cascade reservoir group and multi-objective joint scheduling. Therefore, it is necessary to study the evaluation method of the cascade reservoir group, and establish a set of evaluation system in line with the development status, to grasp the scheduling level of the cascade reservoir group, guide the future dispatching work, and promote the improvement of river basin water resources development and utilization efficiency.

## 2 Indicator System

The scheduling results of cascade reservoirs are often affected by the complex effects of internal factors: (1) inflows and their distributions within the year, (2) dispatching mode, (3) hydraulic structures, and external factors: (1) comprehensive utilization requirements, (2) power system load. In order to conduct fair and impartial evaluations, in the construction of the evaluation system, the evaluation of the cascade reservoir group is only aimed at the goal of "evaluating the present and guiding the future". Based on the above considerations, the indicator system is optimized and screened, as shown in Table 1.

### 2.1 Power generation benefit

As a clean energy with relatively mature technology development, hydropower has the characteristics of low cost, high efficiency, clean process and no pollution. Vigorously developing hydropower is a full response to the development of the “high-quality energy system” by the National Energy Administration. After the operation of the cascade hydropower stations, some operating conditions of the power station change. Under this circumstance, it is necessary for the power station to fully understand its own power generation capacity and power generation efficiency, and at the same time, tap the potential of power generation as much as possible, and do a joint dispatch of the cascade reservoirs, compensate each other, avoid water abandonment, enhance power generation stability, improve cascade power generation and power generation quality, ensure safety and stability, and increase the amount of supply to implement the concept of sustainable development.

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**Table 1.** Benefit evaluation index of cascade reservoir group dispatching.

| Attributes                | index  | Code     |
|---------------------------|--|----------|
| Power generation benefits | Power generation completion rate                 | $G_1$    |
|                           | Power generation completion improvement rate     | $G_2$    |
|                           | Relative power generation water consumption rate | $G_3$    |
| Flood control benefits    | Flood reduction rate                             | $G_4$    |
|                           | Water abandonment rate                           | $G_5$    |
|                           | Flood utilization rate                           | $G_6$    |
| Ecological benefits       | Ecological flow status satisfaction rate         | $G_7$    |
| Water supply benefits     | Water supply guarantee rate                      | $G_8$    |
|                           | Water shortage rate                              | $G_9$    |
|                           | Water supply satisfaction rate                   | $G_{10}$ |

### 2.1.1 Power generation completion rate $G_1$

The power generation completion rate refers to the ratio of the actual power generation in the operation of the cascade power station to the theoretical power generation, which can be used to measure the actual power generation of the reservoir group relative to the target power generation. Among them, the theoretical power generation is a relatively optimal value [2], and the objective function is set by adding relevant constraints (such as water balance constraint, water storage constraint, output constraint, upstream and downstream water quantity constraint, vibration zone constraint, etc.). Calculate the maximum power generation that can be obtained under the established conditions, and flexibly adjust the constraints to reflect different decision preferences. In the calculation, the actual inbound flow is usually taken as input. This index weakens the impact of inflow runoff and its annual distribution on the results. At the same time, the calculation parameters of the two electrical quantities reflect the operation of the same hydraulic mechanical and electrical equipment, while the power system load, the situation can be added to the constraint, so it can eliminate the influence of some factors other than the scheduling mode. It is recommended that the indicator be evaluated in the year, at least calculated by month.

$$G_1 = \sum_{i=1}^n E_{i,r} / \sum_{i=1}^n E_{i,f} \quad (1)$$

Theoretical power generation

$$\begin{cases} E_{i,f} = \sum K_i Q_{i,f,t} H_{i,f,t} t \\ \text{Restrictions} \end{cases} \quad (2)$$

In the formula:  $G_1$  indicates the rate of completion of power generation;  $E_{i,r}$  is the actual power generation during the assessment period of the  $i$ -th power station;  $E_{i,f}$  is the theoretical power generation during the assessment period of the  $i$ -th power station;  $n$  is the number of power stations included in the assessment ladder, for the single station assessment  $n = 1$ ;  $K_i$  represents the output coefficient of the  $i$ -th power station;  $Q_{i,f,t}$  represents the power generation flow rate of the  $i$ -th power station in  $t$  period;  $H_{i,f,t}$  is the power head of the  $i$ -th power station; period  $t = 1, 2, 3, \dots, T$ ,  $T$  is the total number of time periods calculated ( $T = 12$  when the unit is calculated in months).

### 2.1.2 Power generation completion improvement rate $G_2$

Since the “power generation completion rate” cannot fully characterize the advantages and disadvantages of the scheduling method, for example, for a hydropower station with a target value higher than 95% or a hydropower station with less than 85%, 90% of the “power generation completion rate” has completely different meanings. Therefore, it is necessary to make a longitudinal comparison of the power generation completion rate for many years to have a deeper understanding of the power generation level of the cascade power station [3]. Therefore, the “power generation completion improvement rate” indicator is used to measure the degree of the improvement of power generation completion rate for the cascade reservoir group.

The power generation completion improvement rate is the relative difference between the power generation completion rate in a certain year and the average of the power generation completion rate in the previous five years. When the value is positive, it indicates that the power generation level has increased; when it is negative, it indicates that the power generation level has decreased.

$$\begin{cases} G_2 = (G_1 - \overline{G_1}) / \overline{G_1} \\ \overline{G_1} = (\sum_{t=T-5}^{t=T-1} G_{1,t} - \max G_{1,t} - \min G_{1,t}) / 3 \end{cases} \quad (3)$$

In the formula:  $G_2$  is the power generation completion improvement rate;  $\overline{G_1}$  is the average value of power generation completion rate except the maximum and minimum for the first 5 years of the year;  $G_{1,t}$  is the power generation completion rate of the  $t$ -th assessment period. When calculating the average power generation completion rate, it is required that there is no increase in storage capacity during the calculation period, which causes large fluctuations in the reservoir dispatching level.

### 2.1.3 Relative power generation water consumption rate $G_3$

The power generation water consumption rate represents the amount of water consumed per unit of output or

power generation. In the past, the relative power generation water consumption rate is the ratio of actual water consumption rate to the water consumption rate obtained from the operation chart [4], which does not reflect the idea of optimal scheduling. The smaller the power generation water consumption rate, the higher the utilization efficiency, and the smaller the better the indicator. In order to facilitate the later comprehensive evaluation, it is adjusted to the ratio of the power consumption rate of the theoretical scheduling scheme to the actual water consumption rate, and is constructed as a positive (larger is better) indicator.

$$\begin{cases} G_3 = \left[ \prod_{i=1}^n (\delta_{i,f} / \delta_{i,r}) \right]^{1/n} \\ \delta = W / E = C\eta H \end{cases} \quad (4)$$

In the formula:  $G_3$  is the power generation water consumption rate;  $\delta_{i,f}$  and  $\delta_{i,r}$  are the theoretical power consumption rate and actual power consumption rate of the  $i$ -th power station;  $W$  is the total water consumption of power generation;  $E$  is the power generation;  $\eta$  is the unit's comprehensive efficiency;  $H$  is the power head;  $C$  is a constant whose value is equal to 3600/9.8, and other symbols have the same meaning as before.

The theoretical power generation water consumption rate is calculated by the theoretical scheduling scheme. It can be known from the calculation formula of power generation water consumption rate that it is related to the unit efficiency and the power generation head, and the unit efficiency usually varies nonlinearly with the water head, that is, the unit efficiency and the reservoir scheduling method (water head) affect the result of the index.

## 2.2 Flood control benefit

Safeguarding reservoir safety is the primary task of reservoir flood regulation. Under this premise, the reservoir group should master the scheduling method that makes full use of the flood resources, increase the pre-discharge flow during the flooding up stage, and vacate the reservoir capacity to meet the flood at the same time of power generation. The reclaimed section uses the forecast information to store the flood for subsequent power generation or water supply needs [5]. Therefore, the indicators are constructed in terms of the degree of vulnerability reduction and the degree of resource utilization.

### 2.2.1 Flood reduction rate $G_4$

Through pre-discharge and flood control, the uplifting section reservoir will increase the output to increase the power generation benefit while vacating the storage capacity, increasing the reservoir capacity to provide conditions for subsequent flood storage, which is beneficial to flood control safety and facilitates the realization of flood resources later. Through this kind of scheduling, the whole flood control process is relatively relaxed, and the flood peak flow is weakened. Therefore, the flood peak reduction rate is used to reflect the degree

of flood weakening of the reservoir, while the side view maps the available flood amount of the impoundment. The value is the relative difference between the maximum outflow and the flood peak flow.

$$G_4 = (Q_{in}^{max} - Q_{out}^{out}) / Q_{in}^{max} \quad (5)$$

In the formula:  $G_4$  is the flood reduction rate;  $Q_{in}^{max}$  is the flood peak flow;  $Q_{out}^{out}$  is the maximum outflow or the maximum flow of the downstream control section of the reservoir.

### 2.2.2 Flood utilization $G_6$

Under the premise of ensuring safety, the reservoir dispatching should minimize the abandonment of water and strive for efficient use of water resources. It should be noted that the abandonment of water refers to the amount of water directly discharged from the reservoir. Therefore, the definition of the water abandonment rate is the ratio of the total amount of abandoned water to the total amount of floods in the event of a flood. To more intuitively understand the extent of utilization of flood resources by the reservoir, an index of flood utilization is proposed, which is equal to one minus water abandonment rate.

$$\begin{cases} G_5 = W_s / W \\ G_6 = W_d / W = 1 - G_5 \end{cases} \quad (6)$$

In the formula:  $G_5$  is the rate of water abandonment;  $G_6$  is the flood utilization rate;  $W_s$  is the amount of water discarded;  $W$  is the amount of flood;  $G_6$  is the utilization rate of flood;  $W_d$  is the amount of water used, and the value is the amount of flood minus the amount of discarded water.

## 2.3 Ecological Benefits

The ecological flow status satisfaction rate based on the Tennant method is proposed. The main idea is to use the Tennant simultaneous average ratio method [6] to divide the evaluation period into 12 months, and evaluate the monthly flow conditions of the cascade hydropower stations respectively (as shown in Table 2). Aggregate the indicator value of the ecological environment water demand guarantee degree. The evaluation process is divided into the following four steps:

(1) Calculate the actual monthly average flow rate as a percentage of the average monthly flow rate;

(2) Calculate the number of days when the daily flow of a certain month is greater than or equal to the minimum value of the month flow status, and calculate the time satisfaction rate;

(3) Multiply the calculated values of (1) and (2) to obtain the final percentage value of the month;

(4) After obtaining the monthly indicator values through the above three steps, the geometric mean method is used to calculate the final value of the indicator for the current year.

$$G_7 = \left[ \prod_{i=1}^{12} \left( Q_i / \bar{Q}_i \times N / T \right) \right]^{1/12} \quad (7)$$

In the formula:  $G_7$  is the ecological flow status satisfaction rate;  $Q_i$  is the actual monthly average flow of the  $i$ -th-month evaluation period;  $\bar{Q}_i$  is the average monthly flow of the  $i$ -th month;  $N$  is the number of days when the actual daily average flow of the  $i$ -th month is greater than or equal to the minimum value of the flow status;  $T$  is the  $i$ -th month total number of days.

**Table 2.** River flow conditions based on Tennant method

| Flow conditions | Recommended base flow standard (percentage of monthly average flow rate) |
|-----------------|--|
| Optimum         | 60%~100%   |
| Large           | 30%~60%  |
| Normal          | 20%~30%  |
| Poor            | 10%~20%  |
| Minimum         | ≤10%   |

## 2.4 Water supply benefit

### 2.4.1 Water supply guarantee rate $G_8$

The water supply to the reservoir may include shipping water supply, agricultural water supply, industrial water supply, and domestic water supply, which are determined by the actual utilization of each reservoir. From the time continuity, the stability of the water supply of the reservoir is investigated, and the index of the water supply guarantee rate is set. The value is the ratio of the number of the periods in which the water supply meets the water demand to the number of assessment periods.

$$\begin{cases} G_8 = N_{D < 0} / T \\ D = (q_{o,t} - q_{i,t}) \times t \end{cases} \quad (8)$$

In the formula:  $G_8$  is the water supply guarantee rate;  $N_{D < 0}$  is the total number of periods in which the water shortage is less than 0 (ie, the water supply meets the required water demand);  $D$  is the water shortage;  $q_{o,t}$  is the daily/month water demand for the period;  $q_{i,t}$  is the day/month of the period actual water supply flow.

### 2.4.2 Water supply satisfaction rate $G_9$

The water shortage rate can reflect the lack of quantity of the reservoir water supply, and its value is the ratio of the total water shortage in the assessment period to the total water demand. It is an indicator of the smaller and better type. In order to facilitate the later comprehensive evaluation, the positive (larger and better) indicator of

water supply satisfaction is proposed, which can measure the extent to which the water supply meets the water demand, and the value is the amount of water supply compared to the water required.

$$\begin{cases} G_9 = W_i / W_o \\ G_{10} = W_d / W_o \end{cases} \quad (9)$$

In the formula:  $G_9$  is the water supply satisfaction rate;  $G_{10}$  is the water shortage rate;  $W_d$  is the total water shortage in the assessment period, its value is  $\sum_{t=1}^T D$ ;  $W_i$  is the amount of water supply;  $W_o$  is the amount of water demand.

## 3 Comprehensive Evaluation Model

The comprehensive evaluation is a process of analyzing the relative importance of each indicator and obtaining a comprehensive result. The key is to determine the weight of every index. The evaluation needs to ensure that the importance of each factor is reflected, and the process remains objective and fair. The establishment of weights is actually the embodiment of the values of hydropower stations, which can reflect what the enterprise is concerned about and guide the reservoir to the expected goals. It is a quantitative expression of “evaluating the current and guiding the future”.

As the evaluation of the dispatching benefit of the reservoir group needs to be combined with the actual situation of the year, there are many factors that affect the scheduling result. If the subjective qualitative judgment is included in the evaluation, the content that the operator wants to focus on or the operation of the reservoir group can be highlighted, making the process more flexible, and more likely to be in practical applications.

The Analytic Hierarchy Process (AHP) is a multi-decision method combining qualitative and quantitative, which can transform the abstract subjective cognition into an intuitive figurative score, which is conducive to the mutual comparison between different cognitions. By decomposing complex problems into goals, criteria, indicators, etc., the importance of the elements contained in each layer compared to the target layer is compared. The matrix is constructed with 1 to 9, the maximum eigenvalue of the matrix, and the corresponding eigenvector are the importance order of a layer of elements. The weighted sum method is used to summarize the final weight of the lowest element to the total target. The essence of AHP is the process of mathematics thinking.

The calculation steps are as follows:

(1) Hierarchical decomposition. Determine the evaluation object, decompose the decision steps, and build the hierarchy.

(2) Construct a judgment matrix. The factor contained in a certain level is  $\{w_1, w_2, w_3, \dots, w_n\}$ , which is compared with each other to judge the relative importance of the upper layer. The construction

judgment matrix  $A = (w_{ij})_{m \times m}$ ,  $w_{ij} = 1/w_{ji}$ , its importance degree is shown in Table 3.

(3) Calculation of eigenvalues. The maximum eigenvalue  $\lambda_{max}$  satisfying  $AW = \lambda_{max}W$  and the corresponding eigenvector  $W$  are calculated.

(4) Consistency test. The consistency index is calculated as  $CI = (\lambda_{max} - n) / (n - 1)$ , the consistency ratio is  $CR = CI / RI$ , and  $RI$  is available for the random consistency indicator. When  $CR < 0.1$ , the consistency test is passed.

(5) Determine the weight coefficient. After passing the consistency test, the factor values normalized by the feature vector  $W$  are the weights of the corresponding indicators.

**Table 3.** Judging matrix element scale meaning

| Degree  | meaning   |
|---------|---|
| 1       | Two elements are equally important                |
| 3       | The former is slightly important than the latter  |
| 5       | The former is obviously important than the latter |
| 7       | The former is strongly important than the latter  |
| 9       | The former is extremely important than the latter |
| 2、4、6、8 | Between the above scales                          |

The above steps are performed on the adjacent two layers respectively, and finally the weight of the lowest layer (indicator layer) relative to the highest layer (target layer) is obtained.

## 4 Comprehensive Standards and Evaluation

### 4.1 Evaluation standard

#### 4.1.1 Long sequence data

Collect data, calculate indicators, and calculate the frequency. Mainly divided into 3 steps:

(1) Data collection. After selecting a certain indicator  $G_x$  ( $x=1,2,3,\dots,13$ ) and determining its calculation period, collect relevant measured data. The data is required to be continuous, and there is no obvious impact on the level of reservoir dispatching during the period, such as power station expansion.

(2) Calculation of indicator values. Determine the assessment period (usually on a yearly basis) and calculate the value  $G_x^t$  for each period  $t$  of the indicator.

(3) Frequency calculation. The index is sorted by numerical value, and the frequency of occurrence of each value is calculated by  $P = m / (n + 1)$ , where  $m$  is the serial number of the index value of a period  $g$ , and  $n$  is the number of evaluation periods calculated.

#### 4.1.2 Non-long sequence data

When non-long-term sequence data is available, the standard can be adjusted according to the existing standards, related research, and according to the specific conditions of the reservoir group, so that it can be applied to the evaluation object.

The evaluation criteria are determined to be five grades, and the medium (3 points) means that the result reaches the average dispatching level of the reservoir. The selected indicator frequency value is  $P=50\%$ . For each increase of 1 point, the dispatch result is better than the average level. It is less likely to occur. Each decrease of 1 point indicates that the scheduling result is inferior to the average level, and the probability of satisfying it is large. The upper limit of the rating level is excellent (5 points) and the lower limit is bad (1 point). As shown in Table 4.

**Table 4.** Evaluation standard

| ranking      | Long sequence data | Non-long sequence data  |
|--------------|--------------------|---|
| Excellent /5 | $\geq G_{P=40\%}$  | Meet the premise of existing standards, draw on relevant research data, depending on the actual conditions of the reservoir |
| Good /4      | $\geq G_{P=45\%}$  |   |
| Medium /3    | $\geq G_{P=50\%}$  |   |
| Poor/2       | $\geq G_{P=55\%}$  |   |
| Inferior /1  | $< G_{P=55\%}$     |   |

Note:  $G_p$  indicates the index value when the frequency  $P$  occurs.

### 4.2 Overall rating

After obtaining the scores of individual indicators and the weights of each index, the weighted sum can be used to obtain the overall score of the cascade reservoirs in an assessment period, and the cascade evaluation is obtained by analyzing the evaluation criteria and the current status of the cascades.

$$M = \sum_{i=1}^n M_i \mu_i \quad (10)$$

In the formula:  $M$  is the comprehensive evaluation score;  $M_i$  is the score of the  $i$ -th indicator;  $\mu_i$  is the weight of the  $i$ -th index relative to the target layer;  $n$  is the number of indicators that ultimately participate in the evaluation.

## 5 Conclusions

This paper constructs a multi-objective dispatching benefit evaluation system for cascade hydropower stations covering 10 indicators of power generation, flood control, ecology and water supply, and uses the analytic hierarchy process to quantify the expert's qualitative understanding of the reservoir to solve problem of the value of comprehensive evaluation

weights. When selecting the evaluation criteria, we no longer blindly use the fixed value range as the evaluation scale, but consider the multi-year dispatching level of the power station to use the idea of frequency-distribution calculation to divide the grade scale of each index, making the evaluation system widely application is possible. The evaluation system is based on the cascade reservoir group, the indicators are perfect and representative, the evaluation method is intuitive and easy, the evaluation criteria are flexible, and it has the function of “evaluating now and guiding the future”, which can not only carry out the actual scheduling mode evaluation, but also can be used to assess the pros and cons of different scheduling options.

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