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The Construction of Improved Evaluation Indicator System and Quantitative Method of Hydropower Station Dispatching Scheme

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Abstract: The formulation of hydropower station dispatch plans is a critical task for dispatch personnel. Hydropower stations must balance multiple, often competing, functional objectives, necessitating robust methods to identify optimal scheduling schemes that best satisfy diverse operational requirements. However, existing approaches often lack the capability to dynamically adapt to shifting priorities among competing objectives during critical operational periods like reservoir drawdown. Focusing on the downstream Jinsha River-Three Gorges cascade during the drawdown period, this study constructs an improved evaluation indicator system for scheduling schemes. We propose a dynamic indicator priority adaptive indicator calibration method based on historical completion rate (HCR-DPAICM), integrated with the analytic hierarchy process, to achieve a comprehensive subjective-objective evaluation. Comprehensive evaluation results facilitate the comparison of different scheduling schemes across performance indicators and enable an analysis of the advantages and disadvantages of the HCR-DPAICM method. The research provides a valuable reference for selecting hydropower station scheduling schemes.

Keywords: Scheduling scheme evaluation; Construction of indicator system; Evaluation method; AHP; HCR-DPAICM method.

1 Introduction

Hydropower stations constitute comprehensive facility integrating functions, including power generation, ecological conservation, flood control, and shipping. Developing scheduling plans for such stations requires balancing these interdependent functions amid operational constraints and trade-offs, rendering optimal scheduling a complex challenge. Historically, hydropower station operators evaluated scheduling schemes primarily through empirical experience, calculation results, and total power generation. This approach imposes high demands on dispatchers' expertise while lacking adaptability to evolving scheduling priorities across different periods.

The evaluation and optimization selection of hydropower station dispatch schemes is inherently a multi-objective decision-making problem under multiple constraints such as flood control, power generation, and ecology, with the goals of achieving efficient utilization of hydropower resources, maximization of economic benefits, and minimization of environmental impacts. Current research on evaluating and optimizing dispatch schemes has developed a relatively comprehensive system of multi-objective decision-making methods, primarily categorized into two classes: subjective evaluation methods based on expert experience and objective evaluation methods based on data characteristics [1, 2]. The Analytic Hierarchy Process (AHP) is a representative subjective evaluation method, which achieves the quantitative transformation of qualitative problems by constructing a hierarchical structure of objective layer-criterion layer-indicator layer and pairwise comparison matrices. The AHP is widely applied in the water resources field [3]. Ahmad and Verma [4] successfully assessed the most suitable water storage locations in the Chhattisgarh State, India basin using seven criteria/parameters combined with AHP and the suitability rating index developed by the India Meteorological Science Department (IMSD). Lu et al. [5] employed AHP to evaluate the water environmental carrying capacity of China's Huaihe River Basin; by integrating the water environmental conditions with the basin's regional socio-economic and environmental characteristics, their study revealed an upward trend in the carrying capacity and identified its main constraints. Srdjevic and Medeiros [6] proposed a fuzzy methodology for solving fully structured decision problems with criteria, sub-criteria, and alternatives following AHP logic, applying it to evaluate water management plans in parts of Brazil's Paraguaçu River Basin. Besides AHP, fuzzy mathematics theory is also frequently used to address fuzzy boundary issues in the dispatch process [7–9].

However, existing evaluation methods still face significant limitations when applied to comprehensive, dynamic, and quantitative evaluation of hydropower dispatch schemes. On one hand, subjective methods (e.g., AHP) can establish structured evaluation frameworks but heavily rely on expert experience and judgment, posing persistent risks of excessive subjectivity [10]. On the other hand, objective methods such as entropy weight and TOPSIS determine weights based on data characteristics, but their weight calculations may deviate due to data fluctuations. For instance, significant data volatility can lead to weights that contradict practical realities, or minor fluctuations may cause underestimation of indicators, while dynamically integrating decision-makers' preferences remains challenging. Current methods generally lack a comprehensive evaluation framework capable of adapting dynamically to shifting priorities across dispatch periods, effectively integrating subjective and objective information, and uniformly quantifying and comparing heterogeneous indicators encompassing power generation efficiency, ecological flow, and flood control safety. Particularly, existing models exhibit insufficient capability to adaptively adjust objective function weights to align with real-time engineering requirements, potentially resulting in suboptimal alignment between evaluation outcomes and actual dispatch decisions.

Consequently, although multi-objective optimization methods—such as FLGGP [11], ESS integration and linear weighting [12], IMOCS [13], multi-objective particle swarm optimization [14], and other applications [15–20]—have made progress in seeking Pareto frontiers for dispatch schemes or addressing objective conflicts through dimensionality reduction, how to conduct scientific, comprehensive, and practical evaluations of generated or existing dispatch schemes remains a key challenge. This is especially true for resolving the aforementioned gap in a multi-dimensional, dynamic, and subject-object-integrated evaluation framework. To address this research gap, this study leverages implicit information from historical hydropower station data. By proposing a Dynamic Priority Adaptive Indicator Correction Method (HCR-DPAICM) based on historical completion rates to objectively determine weights for dispatch schemes, it integrates the AHP to achieve a subjective-objective comprehensive evaluation. Considering the multi-functional characteristics of hydropower systems, this research focuses on the cascade reservoir system in the lower Jinsha River. The HCR-DPAICM will be used to evaluate dispatch schemes during the key drawdown operation phase of cascade reservoirs, aiming to identify optimal strategies by comparing multiple dispatch scenarios.

2 Method

2.1 Comprehensive evaluation indicator system for drawdown period

The drawdown period represents a critical phase in reservoir operation cycles, characterized by the controlled lowering of water levels to facilitate subsequent impoundment preparations, maintain ecological equilibrium, and satisfy multifunctional requirements. When establishing the evaluation framework for drawdown period operations, the following aspects necessitate comprehensive consideration.

Power generation constitutes a primary function of hydropower stations, with electricity production serving as the core revenue source. Operational schemes must therefore optimize power generation to maximize economic returns, ensuring investment recovery and sustained operational capacity. As pivotal nodes within power grids, hydropower stations significantly influence regional and national grid security through their generation scheduling. Rational dispatch not only meets peak load demands but also mitigates supply shortages. Consequently, power generation metrics should incorporate total output and water consumption rates to enhance resource utilization efficiency. Additionally, indices such as output stability are essential for energy system security.

Hydropower facilities supplying water often simultaneously support agricultural irrigation, industrial processes, municipal consumption, and downstream ecological flows. Strategic reservoir scheduling is vital to guarantee these needs across seasons, especially during dry periods, thereby underpinning socioeconomic stability. Performance indicators include water supply volume, assurance rate, shortage volume, and deficit severity—collectively reflecting fulfillment levels of downstream water demands.

Ecologically, hydropower operations alter natural hydrological regimes, impacting aquatic and terrestrial ecosystems. Scheduling scheme must preserve ecological base flow to sustain fish migration corridors, reproductive cycles, foraging habitats, and riparian ecosystem integrity. Given that optimal ecological flows occur between defined minimum and maximum thresholds, relevant metrics encompass ecological flow satisfaction rate, boundary compliance like minimum or maximum thresholds, alignment with optimal flow ranges, and ecological water surplus/deficit volumes.

For navigation-oriented hydropower stations, operation directly modulate the upstream and downstream water levels, thereby affecting depth, width, velocity and ultimately navigational safety and efficiency. Ensuring navigability transcends economic benefits, as it critically influences regional logistics and social stability. Navigation satisfaction rates and channel-depth compliance metrics offer direct assessments of hydropower discharges in meeting waterway requirements.

Evaluation of hydropower dispatching schemes requires holistic integration of the aforementioned factors alongside additional considerations. Constraint satisfaction—fundamental to scheme feasibility—determines whether operational safety, generation targets, and practical implementation requirements are met. Thus, constraint violation risks and fulfillment degrees constitute essential indicators. Dispatch schemes may also incorporate metrics for critical temporal node compliance and stability indices for water level fluctuation amplitude and power output. The latter directly impacts structural safety of hydropower facilities and riverbanks, while output stability enhances operational safety and unit management efficiency.

Ultimately, the evaluation system synthesizes power generation metrics like total output and water consumption rate, water supply capacity, ecological compliance, navigational adequacy, constraint adherence, and stability indices to holistically assess dispatch scheme performance.

2.2 Comprehensive evaluation method of hydropower station scheduling

2.2.1 Dynamic Priority Adaptive Indicator Calibration Method Based on Historical Completion Rate

Although there have been many objective comprehensive evaluation methods in the past, they all start from changes in objective data such as entropy weight and variation rate[21, 22]. However, taking ecological flow as an example, the ecological flow is basically fully satisfied throughout the period, so if the indicator is only based on change, it will be classified as an unimportant indicator, which is unreasonable. Considering the information inherent in historical data, taking the ecological flow as an example, when the dispatcher reduces other benefits such as power generation benefits to meet the satisfaction rate of ecological flow, it is reflected in the data that the satisfaction rate of ecological flow increases while the power generation decreases. At this time, it can be considered that the importance of the satisfaction rate of ecological flow is higher than that of power generation. Following this approach, all related indicators are transformed into benefit-type completion rate indicators, and the weights are obtained according to the following steps:

1) Calculate the historical completion rates of all indicators among different years. And compute the mean and standard deviation of the historical completion rates for each indicator, denoted as $[\mu_1,\mu_2,\ldots,\mu_n]$ and $[\sigma_1,\sigma_2,\ldots,\sigma_n]$ respectively.

2) With reference to Markowitz's mean-variance portfolio model[23], the utility function U is calculated according to the mean and standard deviation:

$$U_j=\mu_j-\frac{1}{2}\lambda\sigma_j^2 \tag{1}$$

Where, λ is the risk aversion coefficient, the higher the value, the lower the weight of proving greater volatility. In order not to make the standard deviation size excessively affect the coefficients generated by the mean, according to the research results of Barberis and Huang[24], λ takes 3.

3) Determination of the initial weight. The initial weight is obtained according to the utility function result in the following formula:

$$w_j=U_j/\sum U_i \tag{2}$$

Where, w_j represents the specific weight of various indicators. Forming the initial weight matrix $w_s=[w_1, w_2, \ldots, w_n]$.

4) Correction of weights. When an indicator may have limited importance but is easy to satisfy, its historical completion rate will be relatively high, and the indicator may be mistakenly considered as highly important. Therefore, to avoid errors in the importance judgment of simple indicators, they are corrected. The specific method of correction is:

Step One: For a certain indicator m, calculate all the indicator completion rate matrices $[\alpha_1^s,\alpha_2^s,\ldots,\alpha_n^s]$, $[\alpha_1^{s-1},\alpha_2^{s-1},\ldots,\alpha_n^{s-1}]$ and in the period s with increased completion rates and its previous time period s-1. Calculate the unit loss of other indicators when the completion rate of this indicator increases:

$$l_j^m=\begin{cases}0 & \alpha_j^s<\alpha_j^{s-1}\\ (\alpha_j^s-\alpha_j^{s-1})/(\alpha_m^s-\alpha_m^{s-1}) & \alpha_j^s\geq\alpha_j^{s-1}\end{cases} \tag{3}$$

Step Two: From Step One, the influence matrix $R_{n\times n}$ constructed by all indicators can be obtained.

$$R_{n\times n} = \begin{bmatrix} l_1^1 & \cdots & l_1^n \\ \cdots & l_m^m & \cdots \\ l_n^1 & \cdots & l_n^n \end{bmatrix}$$

Calculate the sum of unit loss for each indicator:

$$S_j = \sum_{1}^{n} l_j^i \tag{4}$$

Step 3: To avoid the occurrence of 0 in the final weight, the influence matrix is normalized by Eq. (5):

$$S'_j = e + (1-e)\frac{S_j - S_{\min}}{S_{\max} - S_{\min}} \tag{5}$$

At this point, the elements $w_c{}^j$ in the calibration weight matrix w_c are:

$$w_c^j = \frac{S'_j}{\sum S'_j} \tag{6}$$

Step 4, the final weight matrix is

$$w_e = w_s * w_c \tag{7}$$

2.2.2 Analytic Hierarchy Process

Among traditional decision-making methods, multi-objective dispatching decision-making approaches such as the AHP are commonly utilized.

The AHP decomposes complex decision-making problems into a multi-level hierarchical structure, including the highest level (overall goal), intermediate levels (criteria), and lowest level (alternatives)[25-27]. Key computational steps are as follows:

1) Hierarchical Model Construction

Define the hierarchy by categorizing objectives, criteria, and alternatives into distinct levels.

2) Judgment Matrix Formulation

Establish pairwise comparison matrices using Saaty's 1–9 scale (Table 1) to quantify the relative importance of elements. For factors i and j, the matrix element a_{ij} follows:

- $a_{ij} = 1$:Equal importance
- $a_{ij} = 9$:Extreme importance of i over j
- Intermediate values (2, 4, 6, 8) represent gradations.

3) Consistency Validation

Calculate the consistency index (CI):

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{8}$$

Where, λ_{max} is the largest eigenvalue of the matrix and n is the matrix order.

Compare *CI* with the random consistency index (*RI*) (Table 2). The consistency ratio ($CR = CI/RI$) must satisfy $CR<0.1$.

4) Hierarchical Weight Synthesis

Aggregate weights from all levels to determine the global priority of alternatives relative to the overall goal.

Table 1 Saaty’s Scale for Pairwise Comparisons

Relative Importance	Value
Equal	1
Moderate	3
Strong	5
Very strong	7
Extreme	9
Intermediate values	2,4,6,8

Table 2 Average RI values

Matrix order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.2.3 Comparison of methods

To address the subjective limitations of the traditional AHP in determining indicator weights, the HCR-DPAICM method proposed in this study achieves a data-driven objective evaluation. By analyzing the decision-making patterns implicit in historical scheduling schemes, this method constructs an indicator importance quantification approach based on historical completion rates. Compared with the inherent shortcomings of AHP, which relies on expert experience to build judgment matrices, HCR-DPAICM not only avoids cognitive biases and fuzziness risks caused by human subjective judgments but also captures schedulers’ implicit preference shifts in different scenarios through its dynamic weight adjustment mechanism.

3 Case Study

Taking the cascade reservoirs of the lower Jinsha River - the Three Gorges cascade as the research object, this study uses the actual operation plan and optimized operation plan of a certain year's recession period as examples. The geographical location of the selected research object is shown in Figure 1. Among them, the boundary conditions and incoming water of the two operation plans are consistent, both are on a daily scale, and the time span is from early January to late June. The optimized scheduling scheme aims to maximize power generation and is calculated using a solution algorithm based on Mixed Integer Quadratic Cone Programming[28]. Figure 2 shows the water level flow and output diagram of the actual scheduling process and Figure 3 shows the optimized scheduling process water level flow- output. The table 3 below presents the values of the evaluation indicators for the two schemes. The selection of the recession period (January to June) for this case study is grounded in its critical hydrological and operational significance for large-scale cascade hydropower systems in the Yangtze River Basin. As a transitional phase from high-water storage to seasonal drawdown, this period inherently demands complex trade-offs between maximizing power generation and conserving reservoir storage for impending flood control and water supply needs. The January–June timeframe encapsulates the entire reservoir drawdown trajectory. Importantly, the hydro-meteorological conditions during this period reflect typical dry-season patterns in the region, creating an ideal controlled environment to isolate and evaluate scheduling efficacy without the confounding effects of extreme weather events. By comparing actual and optimized operations under identical hydrologic boundaries, this representative phase rigorously validates the proposed indicator system’s capacity to quantify operational trade-offs, particularly in balancing economic objectives with risk management imperatives.

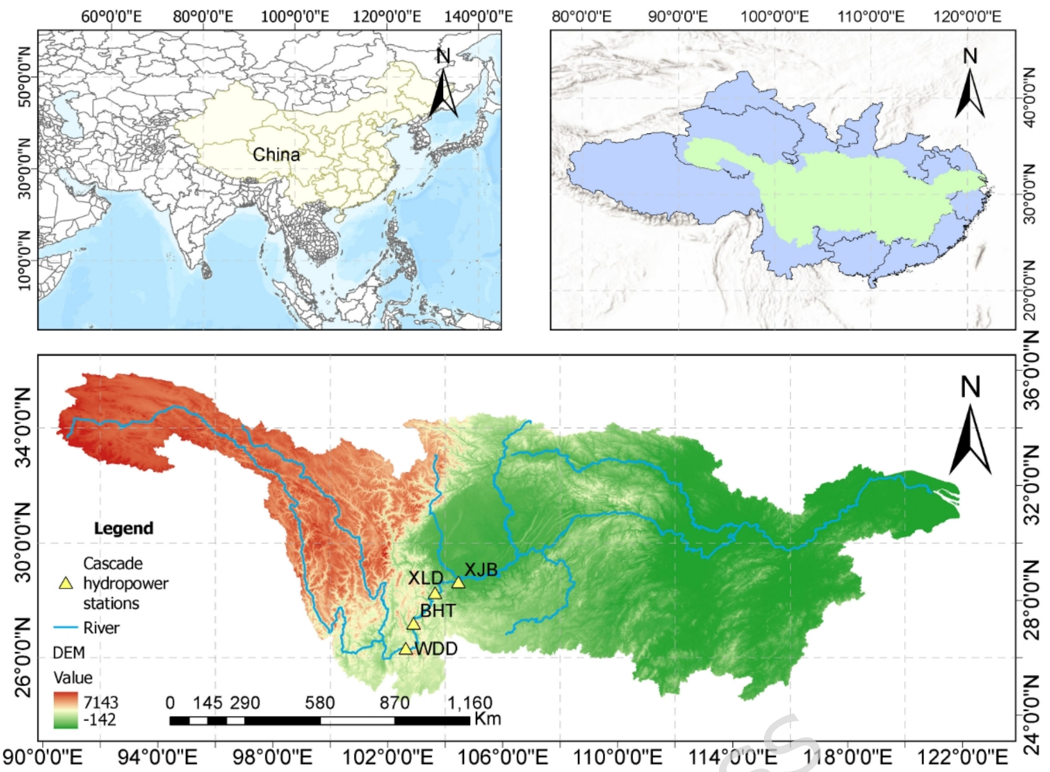

Fig.1 Reservoir location map The base map was generated using ArcGIS Pro software (version 3.6; URL: https://www.esri.com).

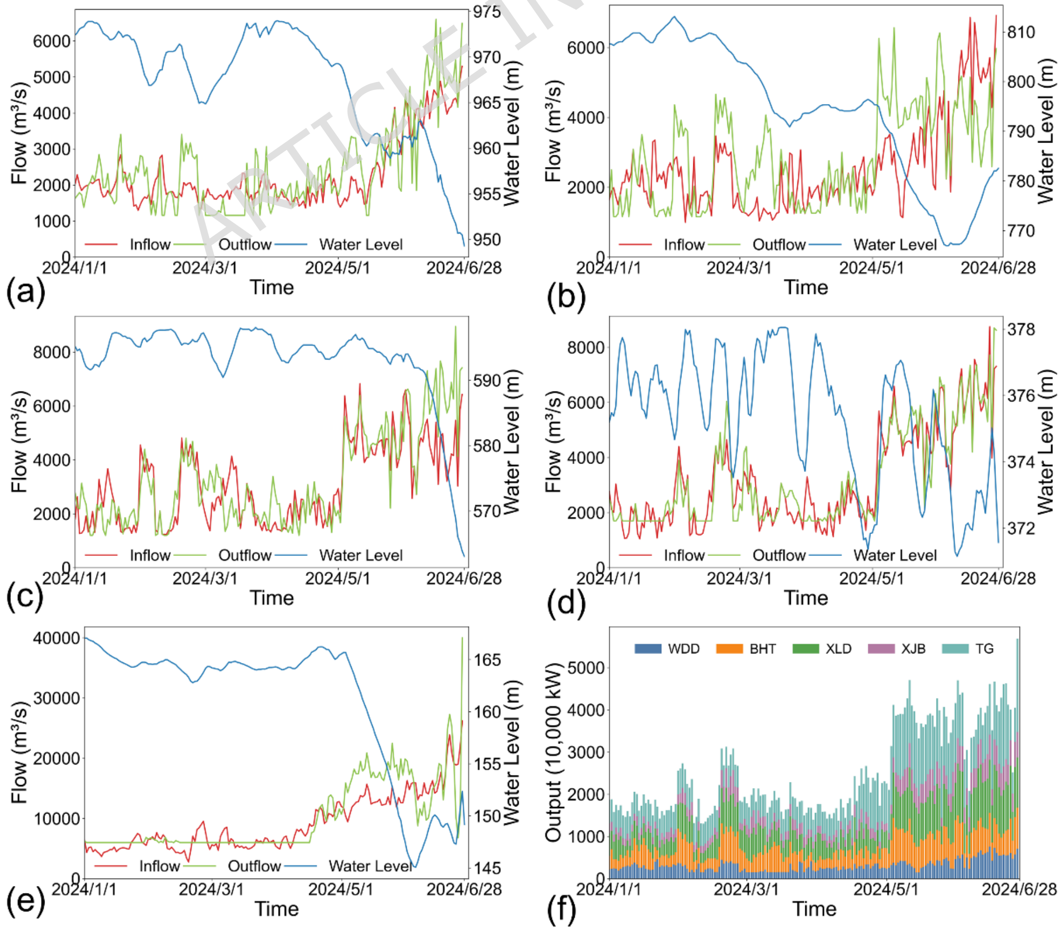

Fig.2 The water level flow and output diagram of the actual scheduling process

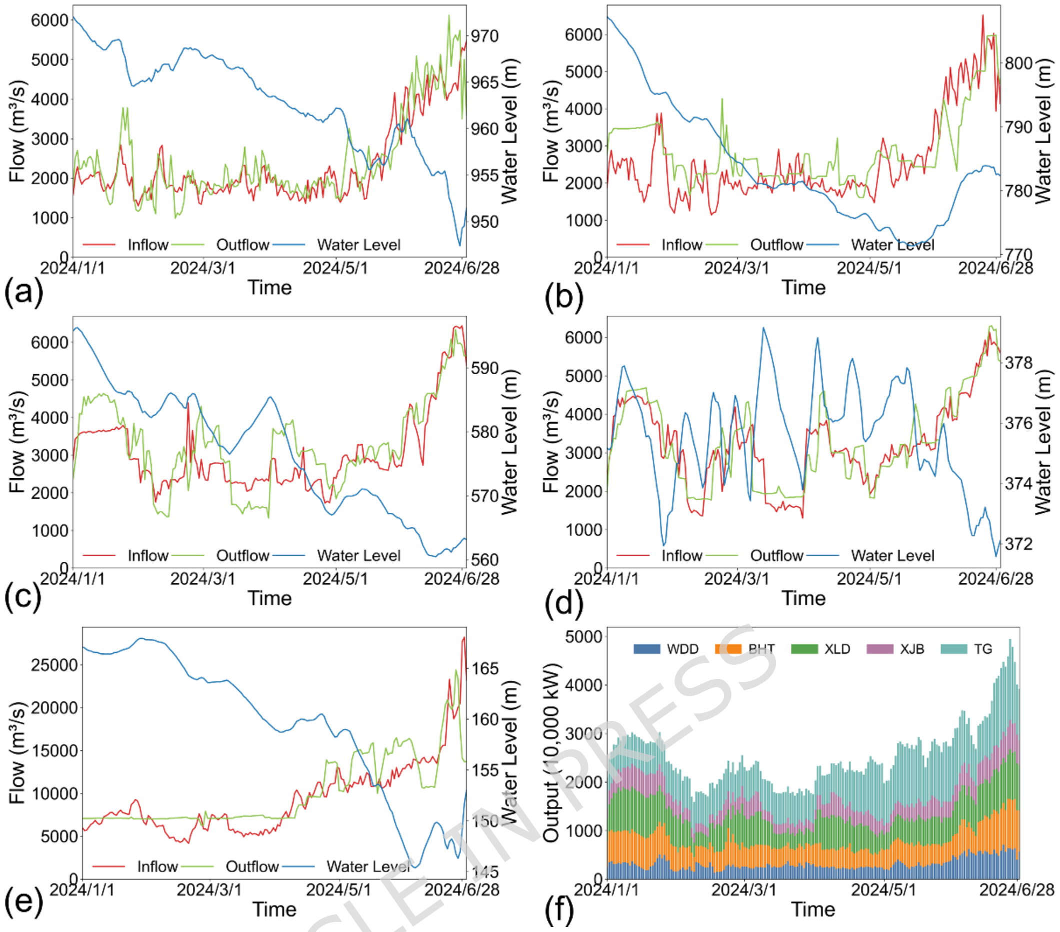

Fig.3 Optimized Scheduling Process Water Level Flow- Output Diagram

Table 3 Statistics of Evaluation Indicators for Each Plan

Evaluation Indicator Total	Scheduling Plan	Reservoir					Sum (or average)
		Wudongde	Baihetan	Xiluodu	Xiangjiaba	Three Gorges	
Power Generation (billion kWh)	Actual scheduling	13.84	22.03	25.61	14.38	36.24	112.1
	Optimal scheduling	14.17	21.95	27.64	13.56	36.4	113.7
Water Consumption Rate	Actual scheduling	7.67	5.71	5.61	9.9	11.85	8.15
	Optimal scheduling	7.4	5.59	5.21	10.29	11.63	8
Output Guarantee Rate	Actual scheduling	0.82	0.29	0.82	0.79	1	0.74
	Optimal scheduling	0.71	0.38	0.87	0.6	1	0.71
Recession Speed	Actual scheduling	0.35	0.33	3.44	2.36	1.08	1.51
	Optimal scheduling	0.44	0.50	3.60	2.49	1.11	1.63
Ecological Flow Satisfaction Rate	Actual scheduling	0.97	1	0.96	1	1	0.98
	Optimal scheduling	1	0.93	1	1	1	0.99
Destruction of Ecological Flow Boundaries	Actual scheduling	0	1	0	1	1	0.60
	Optimal scheduling	1	0	1	1	1	0.80
Ecological Overflow Volume (billion m³)	Actual scheduling	0	0	0	0	0	0
	Optimal scheduling	0	0	0	0	0	0
Ecological Water Deficit (billion m³)	Actual scheduling	361	0	630	0	0	991
	Optimal scheduling	0	117	0	0	0	117
The satisfaction of constraint risk	Actual scheduling	0.7	0.68	0.7	0.71	0.69	0.7
	Optimal scheduling	0.66	0.68	0.53	0.71	0.74	0.66
Condition of constraint satisfaction	Actual scheduling	0	1	1	1	1	0.8
	Optimal scheduling	1	1	1	1	1	1
The key nodes satisfaction	Actual scheduling	1	1	1	1	1	1
	Optimal scheduling	1	1	1	1	1	1
Stationarity	Actual scheduling	0.69	0.47	0.65	0.07	0.81	0.54
	Optimal scheduling	0.44	0.67	0.32	0.39	0.57	0.48

4 Results and Discussion

The HCR-DPAICM method is calculated based on historical data, statistically analyzing the completion rate at the cascade hydropower stations over the past 10 years during the low-flow period from January to June. Among them, due to the varying lengths of time since the establishment of the power stations, some stations lack data for certain periods. Therefore, when calculating the completion rate, only the average data from the five cascade hydropower stations with actual data is used. Figure 4 shows the results of the historical completion rate for each indicator. Based on the aforementioned calculation steps, the loss rates of various indicators were computed. And the result of Loss Amount for Each Indicator is shown in Figure 5. Among them, some indicators had a full time period of 1, making it impossible to calculate the corresponding loss rate. In such cases, the mean value of the indicator was used as a substitute. The final calculated weights are presented in Table 9. The meanings of I1~I20 in Figures 4~6 are shown in Table 11.

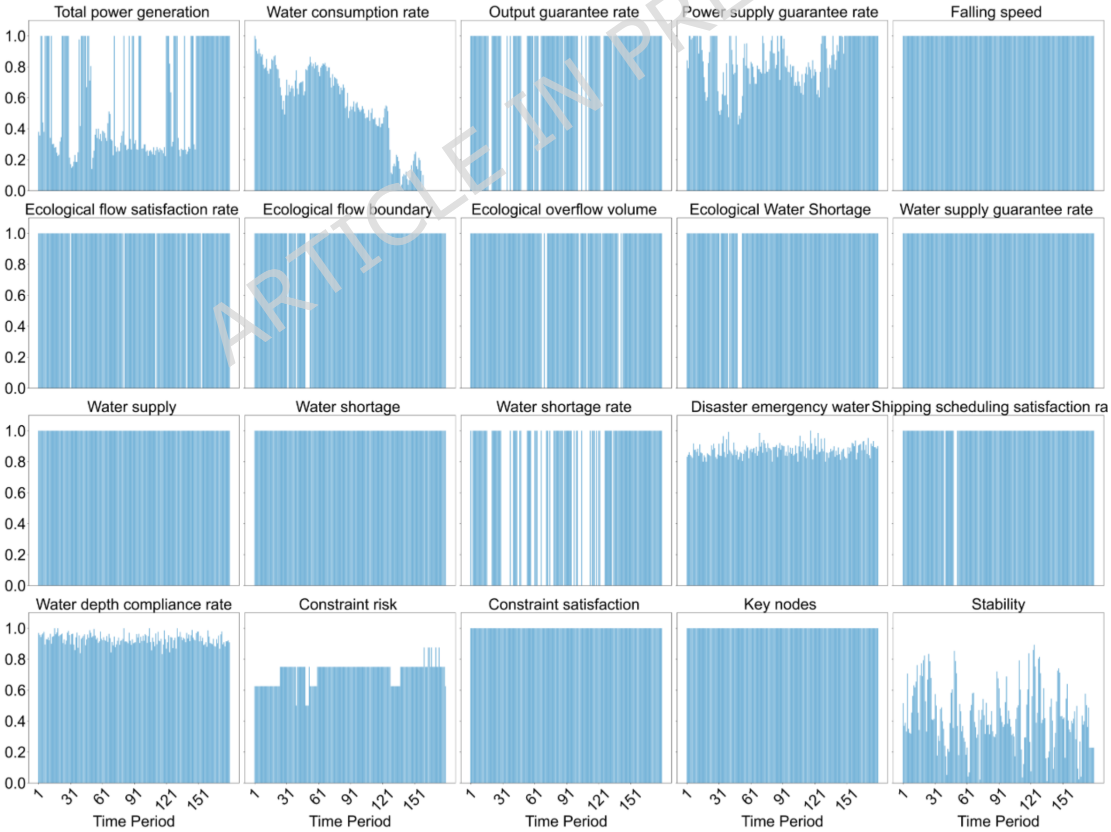

Fig.4 Results of the Historical Completion Rate for Each Indicator

	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	I20
I1	1.00	0.26	0.60	0.00	-9.62	2.19	2.19	0.33	0.25	0.00	-0.33	0.33	0.00	-0.41	0.00	0.00	0.02	0.00	0.00	-8.59
I2	5.61	1.00	-7.18	0.00	-4.16	0.16	0.16	1.41	1.01	0.00	-1.41	1.41	0.00	0.08	0.00	0.00	0.65	0.00	0.00	-0.12
I3	0.12	-0.05	1.00	0.00	0.69	0.08	0.08	-0.10	0.08	0.00	0.10	-0.10	0.00	-0.01	0.00	0.00	0.02	0.00	0.00	-0.03
I4	0.61	0.98	0.82	1.00	0.68	0.97	0.97	0.71	0.98	1.00	0.29	0.71	1.00	0.63	1.00	1.00	0.72	1.00	1.00	0.43
I5	0.19	-0.05	0.43	0.00	1.00	0.05	0.05	-0.09	0.05	0.00	0.09	-0.09	0.00	-0.01	0.00	0.00	0.01	0.00	0.00	0.06
I6	0.21	0.00	0.33	0.00	0.33	1.00	1.00	-0.12	0.33	0.00	0.12	-0.12	0.00	0.01	0.00	0.00	0.04	0.00	0.00	-0.19
I7	0.21	0.00	0.33	0.00	0.33	1.00	1.00	-0.12	0.33	0.00	0.12	-0.12	0.00	0.01	0.00	0.00	0.04	0.00	0.00	-0.19
I8	-4.41	0.32	-2.56	0.00	-5.93	-1.75	-1.75	1.00	-0.34	0.00	-1.00	1.00	0.00	-0.01	0.00	0.00	-0.13	0.00	0.00	1.47
I9	0.33	-0.05	0.50	0.00	0.50	0.50	0.50	-0.16	1.00	0.00	0.16	-0.16	0.00	0.00	0.00	0.00	0.25	0.00	0.00	-0.20
I10	0.61	0.98	0.82	1.00	0.68	0.97	0.97	0.71	0.98	1.00	0.29	0.71	1.00	0.63	1.00	1.00	0.72	1.00	1.00	0.43
I11	-0.43	-0.67	2.17	0.00	4.69	1.30	1.30	-1.00	0.71	0.00	1.00	-1.00	0.00	-0.08	0.00	0.00	0.17	0.00	0.00	-1.76
I12	-4.41	0.32	-2.56	0.00	-5.93	-1.75	-1.75	1.00	-0.34	0.00	-1.00	1.00	0.00	-0.01	0.00	0.00	-0.13	0.00	0.00	1.47
I13	0.61	0.98	0.82	1.00	0.68	0.97	0.97	0.71	0.98	1.00	0.29	0.71	1.00	0.63	1.00	1.00	0.72	1.00	1.00	0.43
I14	-9.27	2.08	11.37	0.00	-22.98	-1.83	-1.83	0.46	-0.22	0.00	-0.46	0.46	0.00	1.00	0.00	0.00	0.24	0.00	0.00	25.32
I15	0.61	0.98	0.82	1.00	0.68	0.97	0.97	0.71	0.98	1.00	0.29	0.71	1.00	0.63	1.00	1.00	0.72	1.00	1.00	0.43
I16	0.61	0.98	0.82	1.00	0.68	0.97	0.97	0.71	0.98	1.00	0.29	0.71	1.00	0.63	1.00	1.00	0.72	1.00	1.00	0.43
I17	0.74	-0.23	-0.36	0.00	0.36	0.36	0.36	-1.01	0.73	0.00	1.01	-1.01	0.00	-0.15	0.00	0.00	1.00	0.00	0.00	0.18
I18	0.61	0.98	0.82	1.00	0.68	0.97	0.97	0.71	0.98	1.00	0.29	0.71	1.00	0.63	1.00	1.00	0.72	1.00	1.00	0.43
I19	0.61	0.98	0.82	1.00	0.68	0.97	0.97	0.71	0.98	1.00	0.29	0.71	1.00	0.63	1.00	1.00	0.72	1.00	1.00	0.43
I20	3.84	-0.19	1.20	0.00	1.63	-0.02	-0.02	-0.86	-0.02	0.00	0.86	-0.86	0.00	0.09	0.00	0.00	-0.08	0.00	0.00	1.00

Fig.5 Results of Loss Amount for Each Indicator

The evaluation indicators during the recession period include five aspects: power generation, water supply, ecology, navigation, and others. Within "others," it includes indicators related to drawdown, constraint risk, constraint satisfaction, key nodes, and stability. Since there are numerous sub-indicators within each category, and it's difficult to compare the importance of sub-indicators between different categories, the weights for power generation, water supply, ecology, navigation, and others are first determined separately. Due to the relative importance of indicators like drawdown speed, constraint risk, constraint satisfaction, key nodes, and stability in the "others" category, these indicators are compared individually with those from other categories.

Referring to the evaluation of each index in previous studies, and combining with the opinions of dispatching experts, each index is compared and assigned one by one, and the judgment matrix in the fluctuation period is obtained as shown in Table 4. Among them, it is believed that key nodes, water supply, ecology, and navigation channels need to be satisfied first, hence they are considered equally important, with the judgment coefficient being 1 for each; while the importance of stability is relatively low, so it is below 1 compared to other indicators; the power generation indicator is considered less than priority indicators such as water supply but higher than drawdown, constraint risk, and other indicators; constraint satisfaction is considered only secondary to priority indicators but higher than power generation and other indicators. Among them, the judgment matrix among the sub indicators of power generation, ecology and water supply is shown in Table 5-7 below. Table 8 shows that the consistency ratio (CR) values are all less than 0.1, indicating that the consistency of the judgment matrix is reasonable. The final calculated weights are shown in the table 9.

Table 4 Drawdown period macro-indicator judgment matrix

Indicator	Power generation	Water supply	Ecological	Channel	Fall speed	Constraint risk	Constraint satisfaction	Key nodes	Stability
Power generation	1.00	0.14	0.14	0.14	6.00	2.00	0.20	0.14	8.00
Water supply	7.00	1.00	1.00	1.00	9.00	8.00	3.00	1.00	9.00
Ecological	7.00	1.00	1.00	1.00	9.00	8.00	3.00	1.00	9.00
Channel	7.00	1.00	1.00	1.00	9.00	8.00	3.00	1.00	9.00
Fall speed	0.17	0.11	0.11	0.11	1.00	0.20	0.11	0.11	2.00
Constraint risk	0.50	0.13	0.13	0.13	5.00	1.00	0.13	0.13	6.00
Constraint satisfaction	5.00	0.33	0.33	0.33	9.00	8.00	1.00	0.33	9.00
Key nodes	7.00	1.00	1.00	1.00	9.00	8.00	3.00	1.00	9.00
Stability	0.13	0.11	0.11	0.11	0.50	0.17	0.11	0.11	1.00

Table 5 Power generation indicator judgment matrix

Indicator	Total Power Generation	Water Consumption Rate	Power Output Guarantee Rate	Power Supply Guarantee Rate on Important Holidays

Total Power Generation	1.00	3.00	1.00	7.00
Water Consumption Rate	0.33	1.00	0.14	1.00
Power Output Guarantee Rate	1.00	7.00	1.00	7.00
Power Supply Guarantee Rate on Important Holidays	0.14	1.00	0.14	1.00

Table 6 Ecological indicator judgment matrix

Indicator	Ecological flow satisfaction rate	Ecological flow boundary destruction	Ecological overflow volume	Ecological water shortage volume
Ecological flow satisfaction rate	1.00	3.00	5.00	3.00
Ecological flow boundary destruction	0.33	1.00	3.00	1.00
Ecological overflow volume	0.20	0.33	1.00	0.33
Ecological water shortage volume	0.33	1.00	3.00	1.00

Table 7 Water Supply Indicator Judgment Matrix

Indicator	Water supply guarantee rate	Water supply volume	Water shortage volume	Water shortage rate	Disaster emergency water supply volume
Water supply guarantee rate	1.00	2.00	2.00	3.00	5.00
Water supply volume	0.50	1.00	1.00	2.00	4.00
Water shortage volume	0.50	1.00	1.00	2.00	4.00
Water shortage rate	0.33	0.50	0.50	1.00	3.00
Disaster emergency water supply volume	0.20	0.25	0.25	0.33	1.00

Table 8 Consensus indicators results matrix

Indicator	λ_{max}	CI	RI	CR

Overall	10.05	0.13	1.46	0.09
Power Generation	6.31	0.06	1.26	0.05
Ecological	4.04	0.01	0.89	0.02
Water Supply	6.06	0.01	1.26	0.01

The comprehensive weight evaluation is based on AHP and HCR-DPAICM to conduct a comprehensive evaluation of the plan from both subjective and objective perspectives, with both methods calculating 50% of the weight for the same indicator. The final comprehensive evaluation weights are presented in the table 10. The changes in weights corresponding to each indicator are shown in Figure 6.

The trends of weights calculated by the AHP and HCR-DPAICMs are basically consistent. However, for some specific indicators such as the power supply guarantee rate during important holidays and critical nodes, due to the historical completion rate of these indicators being basically 1 for all time periods, the HCR-DPAICM mistakenly believes that the weights of these indicators are relatively high. After the comprehensive weight calculation, its trend is more consistent with that of the AHP, therefore, it can be considered that both the comprehensive weights and the weights of the AHP are relatively reasonable.

Compared to the more subjective AHP, some of the simpler and easier-to-satisfy indicator weights in the HCR-DPAICM will have obvious differences. For example, the weight of the HCR-DPAICM on indicators such as water consumption rate and the power supply guarantee rate on important holidays is significantly higher than that of the AHP. The main reason is that the historical completion rates of these indicators are very high. Although the calibration has been somewhat reduced, it is still relatively high compared to the AHP. In addition, the HCR-DPAICM has a significant reduction in the extreme values of weights. For instance, the weight of the key nodes calculated by the AHP is 0.208, while the result obtained by the HCR-DPAICM is 0.089, which is the same size as constraints satisfaction, shipping indicators, and others.

Through the above analysis, it can be seen during HRC calculation, due to the existence of the maximum satisfaction threshold of 1 in the calculation of the historical completion rate of indicators, the comparability between some indicators is not strong, and relying solely on data may not necessarily meet the needs of schedulers. The comprehensive evaluation indicator integrates both objective and subjective weights, and its trend is close to the subjective ideas of schedulers such as AHP, and it has a certain improvement for the extreme values and minimum values in the indicators, enhancing the comparability between different indicators.

In calculating the score, first calculate the scores of each indicator, S_i, and multiply them by the weight of different methods, w_i, to get the scores of each method under these indicators.

Table 9 Weight calculation result

Indicators	AHP	HCR-DPAICM	Comprehensive weight
Total power generation	0.019	0.004	0.010
Water consumption rate	0.004	0.011	0.008
Output guarantee rate	0.023	0.029	0.022
Power supply guarantee rate	0.003	0.089	0.046
Falling speed	0.066	0.089	0.078
Ecological flow satisfaction rate	0.039	0.063	0.051
Ecological flow boundary	0.039	0.001	0.020
Ecological overflow volume	0.022	0.089	0.056
Ecological Water Shortage	0.009	0.051	0.030
Water supply guarantee rate	0.018	0.017	0.018
Water supply	0.103	0.047	0.076
Water shortage	0.040	0.047	0.044
Water shortage rate	0.016	0.001	0.008
Disaster emergency water supply	0.040	0.049	0.045
Shipping scheduling satisfaction rate	0.149	0.089	0.119
Water depth compliance rate	0.050	0.089	0.070
Constraint risk	0.038	0.034	0.036
Constraint satisfaction	0.112	0.089	0.101
Key nodes	0.197	0.089	0.144
Stability	0.015	0.022	0.019

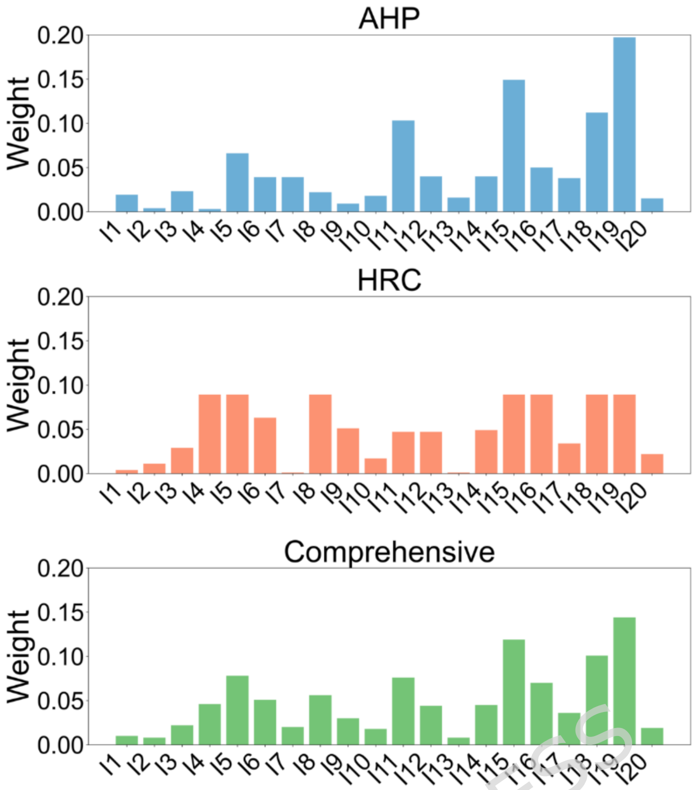

Fig.6 Changes in the weight of each indicator

Table10 Indicator score calculation results

Indicator	Indicator calculation		AHP score		HCR-DPAICM score		comprehensive weight score	
	Actual scheduling	Optimiza-tion scheduling	Actual scheduleing	Optimization scheduleing	Actual scheduling	Optimization scheduling	Actual scheduling	Optimization scheduling
Total power generation	0.986	1.000	0.018	0.019	0.004	0.004	0.010	0.010
Water consumption rate	0.982	1.000	0.004	0.004	0.011	0.011	0.008	0.008
Output guarantee rate	0.744	0.712	0.017	0.016	0.022	0.021	0.016	0.016
Power supply guarantee rate in important holidays	1.000	1.000	0.003	0.003	0.089	0.089	0.046	0.046
Falling speed	1.000	1.000	0.066	0.066	0.089	0.089	0.078	0.078

Ecological flow satisfaction rate	1.000	1.000	0.039	0.039	0.063	0.063	0.051	0.051
Ecological flow boundary	1.000	1.000	0.039	0.039	0.001	0.001	0.020	0.020
Ecological overflow volume	1.000	1.000	0.022	0.022	0.089	0.089	0.056	0.056
Ecological Water Shortage	1.000	1.000	0.009	0.009	0.051	0.051	0.030	0.030
Water supply guarantee rate	0.680	0.780	0.012	0.014	0.011	0.013	0.012	0.014
Water supply	0.985	0.986	0.101	0.101	0.046	0.046	0.075	0.075
Water shortage	0.600	0.800	0.024	0.032	0.028	0.037	0.026	0.035
Water shortage rate	1.000	1.000	0.016	0.016	0.001	0.001	0.008	0.008
Disaster emergency water supply	1.000	0.847	0.040	0.034	0.049	0.041	0.045	0.038
Shipping scheduling satisfaction rate	1.000	1.000	0.149	0.149	0.089	0.089	0.119	0.119
Water depth compliance rate of waterway maintenance	1.000	1.000	0.050	0.050	0.089	0.089	0.070	0.070
Constraint risk	0.696	0.665	0.026	0.025	0.024	0.023	0.025	0.024
Constraint satisfaction	0.800	1.000	0.089	0.112	0.071	0.089	0.081	0.101
Key nodes	1.000	1.000	0.197	0.197	0.089	0.089	0.144	0.144
Stability	0.539	0.477	0.008	0.007	0.012	0.010	0.010	0.009
Total	18.012	18.267	0.929	0.954	0.928	0.945	0.930	0.952

Table11 Indicator Abbreviations in Figures 4 to 6

Indicators	Abbreviations in Figures 4 to 6
Total power generation	I1
Water consumption rate	I2
Output guarantee rate	I3
Power supply guarantee rate in important holidays	I4
Falling speed	I5
Ecological flow satisfaction rate	I6
Ecological flow boundary	I7
Ecological overflow volume	I8
Ecological Water Shortage	I9
Water supply guarantee rate	I10
Water supply	I11
Water shortage	I12
Water shortage rate	I13
Disaster emergency water supply	I14
Shipping scheduling satisfaction rate	I15
Water depth compliance rate of waterway maintenance	I16
Constraint risk	I17
Constraint satisfaction	I18
Key nodes	I19
Stability	I20

Comprehensive evaluation results reveal distinct performance characteristics across operational schemes. Under identical boundary conditions and constraints, the optimized scheme demonstrates a reduced water consumption rate alongside increased average output and total power generation relative to the actual drawdown process. However, these improvements remain marginal, yielding comparable scores for power generation metrics. Notably, the optimized scheme exhibits a diminished output guarantee rate, resulting in a lower score for this particular indicator. Regarding water supply, all schemes fully satisfy downstream demand with consistent performance ratings. Ecologically, the optimized scheme achieves a 98.6% ecological flow satisfaction rate—surpassing the actual scheme—yet incurs slightly greater cumulative ecological water deficit, leading to a marginal score reduction. No ecological overflow occurs in any scheme, maintaining uniform maximum scores for this parameter.

All schemes meet navigability criteria with perfect scores. For constraint compliance, the optimized scheme operates closer to constraint boundaries, increasing violation risk and marginally lowering its score. Crucially, while constraint violations occur in the actual scheduling process, the optimized scheme maintains full compliance. Adaptive adjustments in the optimized scheme enhance power generation, ecological, and navigation outcomes but reduce stability of water levels, flow rates, and power output, consequently lowering its stability score. Key temporal node requirements are uniformly satisfied across all schemes. Under multiple evaluation methodologies, optimized scheduling schemes consistently outperform actual schemes, with constraint satisfaction constituting the primary differentiator in overall performance.

5 Conclusion

This study establishes a comprehensive evaluation framework for reservoir scheduling schemes through a case study of the Jinsha River downstream - Three Gorges cascade reservoir system. By synthesizing practical operational constraints and expert domain knowledge, we developed tailored indicator criteria and proposed the HCR-DPAICM to address inherent limitations in conventional evaluation approaches. The integration of AHP with our novel HCR-DPAICM method yields significant methodological advancements: weight calculation results demonstrate that this hybrid approach effectively balances the trade-off between expert subjectivity and objective operational data, moderately elevating weights for readily attainable indicators while substantially mitigating extreme weight distributions observed in standalone AHP applications. Consequently, the generated comprehensive evaluation indices achieve enhanced cross-indicator comparability and operational relevance. Empirical assessments confirm that optimized dispatch schemes deliver superior integrated performance—exhibiting measurable gains in power generation efficiency and constraint compliance despite marginally elevated constraint violation risks when benchmarked against conventional alternatives. Collectively, these contributions provide: (1) objectively verifiable quantitative criteria for comparative analysis of dispatch methodologies, and (2) a robust, generalizable framework for holistic scheme assessment that advances the paradigm of sustainable hydropower operations within complex cascade reservoir systems.

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Data Availability

The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.
Consent to Participate Not applicable.
Consent for Publish Not applicable.

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Wang Huey-Jiun, Zeng Zhi-Teng. A multi-objective decision-making process for reuse selection of historic buildings. *Expert Systems with Applications* **37**, 1241-1249 (2010).

2. Wu Wann-Yih, Sukoco Badri Munir, Li Chia-Ying, Chen Shu Hui. An integrated multi-objective decision-making process for supplier selection with bundling problem. *Expert Systems with Applications* **36**, 2327-2337 (2009).

3. Cabrera Enrique, Jr., Cobacho Ricardo, Estruch Vicent, Aznar Jerónimo. Analytical hierarchical process (AHP) as a decision support tool in water resources management. *Journal of Water Supply: Research and Technology-Aqua* **60**, 343-351 (2011).

4. Ahmad Ishtiyaq, Verma Mukesh Kumar. Application of Analytic Hierarchy Process in Water Resources Planning: A GIS Based Approach in the Identification of Suitable Site for Water Storage. *Water Resources Management* **32**, 5093-5114 (2018).

5. Lu Yan, Xu Hongwen, Wang Yuexiang, Yang Yang. Evaluation of water environmental carrying capacity of city in Huaihe River Basin based on the AHP: A case in Huai'an City. *Water Resources and Industry* **18**, 71-77 (2017).

6. Srdjevic Bojan, Medeiros Yvonilde Dantas Pinto. Fuzzy AHP Assessment of Water Management Plans. *Water Resources Management* **22**, 877-894 (2008).

7. Archibald Thomas W., Marshall Sarah E. Review of Mathematical Programming Applications in Water Resource Management Under Uncertainty. *Environmental Modeling & Assessment* **23**, 753-777 (2018).

8. Jairaj P. G., Vedula S. Multireservoir System Optimization using Fuzzy Mathematical Programming. *Water Resources Management* **14**, 457-472 (2000).

9. Khazaei Bahram, Hosseini Seyed Mahmood. Improving the

performance of water balance equation using fuzzy logic approach. *Journal of Hydrology* **524**, 538-548 (2015).

10. Liu Yan, Eckert Claudia M., Earl Christopher. A review of fuzzy AHPs for decision-making with subjective judgements. *Expert Systems with Applications* **161**, 113738 (2020).

11. Fallah-Mehdipour Elahe, Bozorg-Haddad Omid, Loáiciga Hugo A. Calculation of multi-objective optimal tradeoffs between environmental flows and hydropower generation. *Environmental Earth Sciences* **77**, 453 (2018).

12. Fan Hong, Yuan Qianqian, Cheng Haozhong. Multi-Objective Stochastic Optimal Operation of a Grid-Connected Microgrid Considering an Energy Storage System. *Applied Sciences* **8**, 2560 (2018).

13. Meng Xuejiao, Chang Jianxia, Wang Xuebin, Wang Yimin. Multi-objective hydropower station operation using an improved cuckoo search algorithm. *Energy* **168**, 425-439 (2019).

14. Aghajani Gholamreza, Yousefi Naser. Multi-objective optimal operation in a micro-grid considering economic and environmental goals. *Evolving Systems* **10**, 239-248 (2019).

15. Feng Zhong-kai, Liu Shuai, Niu Wen-jing, Jiang Zhi-qiang, Luo Bin, Miao Shu-min. Multi-Objective Operation of Cascade Hydropower Reservoirs Using TOPSIS and Gravitational Search Algorithm with Opposition Learning and Mutation. *Water* **11**, 2040 (2019).

16. Feng Zhong-kai, Niu Wen-jing, Cheng Chun-tian. Optimization of hydropower reservoirs operation balancing generation benefit and ecological requirement with parallel multi-objective genetic algorithm. *Energy* **153**, 706-718 (2018).

17. Bian Jia-qi, Dong Zeng-chuan, Jia Yi-fei, Zhong Dun-yu. Research on the multi-objective optimal operation of cascade reservoirs in the upper and middle Yellow River basin. *Water Supply* **19**, 1918-1928 (2019).

18. Yu Lei, Wu Xiufeng, Wu Shiqiang, Jia Benyou, Han Guoyi, Xu Peng, Dai Jiangyu, Zhang Yu, Wang Fangfang, Yang Qianqian, Zhou Zehui. Multi-objective optimal operation of cascade hydropower

plants considering ecological flow under different ecological conditions. *Journal of Hydrology* **601**, 126599 (2021).

19. Yu Haojianxiong, Shen Jianjian, Cheng Chuntian, Lu Jia, Cai Huaxiang. Multi-Objective Optimal Long-Term Operation of Cascade Hydropower for Multi-Market Portfolio and Energy Stored at End of Year. *Energies* **16**, 604 (2023).

20. Wei Yiming, Dong Zengchuan. Application of a Novel Jaya Algorithm Based on Chaotic Sequence and Opposition-based Learning in the Multi-objective Optimal Operation of Cascade Hydropower Stations System. *Water Resources Management* **35**, 1397-1413 (2021).

21. Vu Thi T., Tian Gang, Khan Naveed, Zada Muhammad, Zhang Bin, Nguyen Thanh V. Evaluating the International Competitiveness of Vietnam Wood Processing Industry by Combining the Variation Coefficient and the Entropy Method (2019).

22. Chen Zhi-Mou, Yeh Yi-Lung, Chen Ting-Chien. Assessment of a Regional Flood Disaster Indicator via an Entropy Weighting Method. *Natural Hazards Review* **19**, 05018002 (2018).

23. Markowitz Harry M. *Portfolio selection: efficient diversification of investments*. Yale university press (2008).

24. Barberis Nicholas, Huang Ming. Stocks as Lotteries: The Implications of Probability Weighting for Security Prices. *American Economic Review* **98**, 2066-2100 (2008).

25. Saaty Thomas L. Analytic hierarchy process. In: *Encyclopedia of operations research and management science*). Springer (2013).

26. Sullivan William G. *Economic and multiattribute evaluation of advanced manufacturing systems*. Prentice Hall (1989).

27. Crowe Thomas J., Noble James S., Machimada Jeevan S. Multi-attribute analysis of ISO 9000 registration using AHP. *International Journal of Quality & Reliability Management* **15**, 205-222 (1998).

28. Duan Jiefeng, Jiang Zhiqiang. Joint Scheduling Optimization of a Short-Term Hydrothermal Power System Based on an Elite Collaborative Search Algorithm (2022).