Research on the Cascade Operation Mode of Wangfuzhou Section in Danjiangkou Reservoir Based on Ecological Assessment

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Abstract. Since the operation of the Middle Route of the South-to-North Water Diversion Project, numerous changes have occurred in the operational conditions of the Danjiangkou Reservoir, among which the ecological assessment requirements for the lower reaches of the Han River have had the most significant impact on the operation mode of the Danjiangkou Power Plant. This paper establishes a short-term scheduling model and formulates differentiated cascade reservoir scheduling objective functions based on various ecological assessment requirements for the downstream river channels, thereby deriving the daily operation process of the Danjiangkou-Wangfuzhou Reservoir under different operating conditions. The conclusions indicate that the establishment of ecological assessment requirements has weakened the peak shaving capacity of the Danjiangkou Reservoir. However, by leveraging the counter-regulation function of the Wangfuzhou Reservoir, the peak shaving capacity of the Danjiangkou Power Plant within the power grid can be restored. Furthermore, as the canalization process of the lower reaches of the Han River progresses, the Wangfuzhou Reservoir will fully exploit its power generation benefits, and the power generation losses incurred due to its coordination with the peak shaving of the Danjiangkou Reservoir will be compensated. The restoration of the peak shaving capacity of cascade reservoirs facilitates their collaboration with other clean energy sources in undertaking power generation tasks at different times within the power grid, thereby providing favorable support for the multi-energy complementary joint operation of the power grid.

Keywords: Danjiangkou, peak-load regulating capacity, ecological assessment.

Y. Qiu et al. (eds.), *Proceedings of the 2024 7th International Conference on Civil Architecture, Hydropower and Engineering Management (CAHEM 2024)*, Advances in Engineering Research 256,
https://doi.org/10.2991/978-94-6463-650-5_16

1 Introduction

Hydroelectric power represents an environmentally friendly and renewable energy source, characterized by economical operational costs, convenient unit startup and shutdown capabilities, as well as exceptional peak shaving abilities, thereby playing a pivotal role within power grids. Early research primarily focused on mitigating the issue of water abandonment during peak shaving operations in hydropower stations [1]. As the scale of hydropower expanded, investigations shifted towards the coordinated regulation capabilities and efficiency of cascade hydropower systems in balancing large-scale power grids and supporting the integration of renewable energy sources [2], alongside the development of algorithms aimed at reducing the complexity of cascade peak shaving optimization [3]. Currently, the integration and optimal dispatch of large-scale wind, solar, and hydropower renewable energy sources have emerged as a new research frontier [4,5].

The world's total hydropower installed capacity now stands at 1.36 billion kW, with China leading at 391 million kW. In central-east China, conventional hydropower is nearly fully developed (90%), limiting new construction. Thus, restoring hydropower capacity emerges as a new direction [6,7,8]. This study focuses on leveraging cascade reservoir counter-regulation to enhance peak shaving capabilities, ensuring both engineering safety and ecological compliance [9,10].

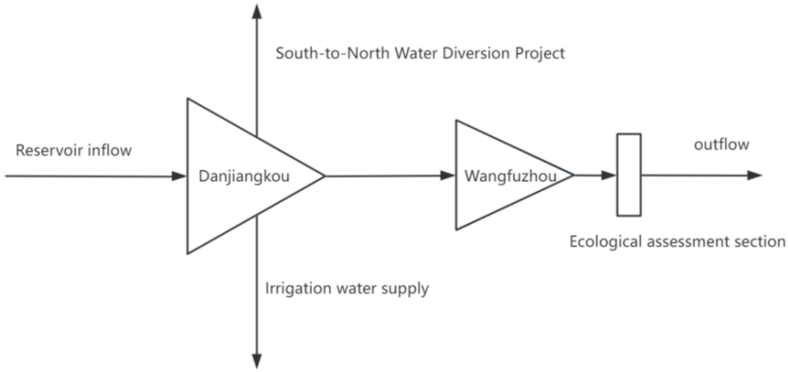

Fig. 1. Topology of cascade reservoir and its relationship with water users

The Danjiangkou Reservoir, initially built for flood control and power generation, now prioritizes water supply for the South-to-North Water Diversion Project while maintaining downstream utilization and power generation [11,12]. The State Council's water pollution prevention plan emphasizes ecological water management. During trial operations, the Danjiangkou Power Plant's peak shaving function was compromised. In 2019, the Yangtze River Water Resources Commission established an ecological assessment section downstream to restore peak shaving capabilities [13]. A joint operation study of Danjiangkou and Wangfuzhou cascade reservoirs aims to analyze their operation under new ecological requirements, utilizing Wangfuzhou's daily regulation to restore Danjiangkou's peak load capacity while ensuring water supply and ecological needs [14,15]. This is crucial for improving power station performance, avoiding unit vibrations, and enhancing generation quality. The cascade's peak load capacity mitigates instability from renewable energy sources, crucial for multi-energy grid integration. With a multi-year storage capacity of 19.05 billion m³ and 900MW installed, Danjiangkou serves as the water source for the diversion project. Wangfuzhou, 30km downstream, offers daily regulation, 28.8 million m³ storage, and 109MW installed capacity.

Figure 1 depicts the cascade reservoirs and their water users.

2 Short Term Scheduling Model and Achievements of Cascade Reservoirs

2.1 Objective Function

The short-term optimization model of cascade power plant should consider many goals such as the maximum power generation or the maximum power generation benefit [16]. This kind of problem can be described as: given the initial reservoir water level, the water consumption in the control period (or the control end of the reservoir water level), under various constraints, find the output process of each power plant, so that the power generation or power generation benefit (peak load capacity) during the control period is maximum [17]. The objective function, denoted as B, can be universally expressed through the following mathematical formulation:

$$Max\ B = \sum_{k=1}^{2}\sum_{t=1}^{T} C_{k,t} \cdot E_{k,t} = \sum_{k=1}^{2}\sum_{t=1}^{T} C_{k,t} \cdot N_{k,t} \cdot \Delta t \tag{1}$$

where $C_{k,t}$ is the electricity price coefficient for time period t of power plant k; $E_{k,t}$ is the power generation of k power plant during time period t; $N_{k,t}$ is the output of k power plant during time period t; $H_{k,t}$, $Q_{k,t}$ represents the power generation head and power generation flow of k power plant during time period t.

With variations in k and t, based on the operational data of the Hubei power grid, the ratio of electricity prices during peak, flat, and off-peak hours is set as 1:0.75:0.5. When hydropower plants engage in system peak shaving, the objective function, guided by the electricity price coefficients, aims to maximize peak shaving capacity. Conversely, from the perspective of energy maximization, where the electricity price coefficient is set to 1, the objective function is formulated to maximize power generation. In the practical operation of the two cascade hydropower plants, due to their distinct roles and responsibilities within the system, Danjiangkou focuses on participating in system peak shaving with the objective of maximizing peak shaving capacity, while Wangfuzhou prioritizes maximizing power generation. Thus, the operation of cascade hydropower plants is characterized by differentiated objectives.

2.2 Constraint Condition

(1) Total water consumption constraint

$$\sum_{t=1}^{T}(Q_{f,t}+Q_{q,t})\Delta t=W_{c,T} \tag{2}$$

where $Q_{k,f,t}$ and $Q_{k,q,t}$ represent the diversion flow rate and the discharged flow rate of K Reservoir in T period, respectively, and $W_{c,T}$ is the total outflow volume of the reservoir during the planning period.

(2) Reservoir water balance equation

$$V_{k,t+1}=V_{k,t}+(I_{k,t}-Q_{k,f,t})\Delta t+\mathrm{W}_{kt} \tag{3}$$

where $V_{k,t}$, $V_{k,t+1}$ are the water storage capacity of k reservoir at the beginning and end of t period respectively; $I_{k,t}$, $W_{k,t}$ are the inflow flow of the k reservoir and other water flows during the t period, respectively.

(3) Reservoir water level or storage capacity constraints

$$Z_{\mathrm{k,min}}\le Z_{k,t+1}\le Z_{\mathrm{k,max}}$$

or

$$V_{\mathrm{k,min}}\le V_{k,t+1}\le V_{\mathrm{k,max}} \tag{4}$$

where $Z_{k,min}$, $V_{k,min}$ are respectively the lowest water level or minimum water storage capacity of the reservoir in the t+1 period of the k power station; $Z_{k,max}$, $V_{k,max}$ are the maximum allowable water storage capacity of the reservoir during t+1 period respectively. The range of water storage is obtained by checking the storage capacity curve of water level.

(4) Power generation output constraint

$$N_{\mathrm{k,t,min}}\le N_{k,t}\le N_{\mathrm{k,t,max}} \tag{5}$$

where $N_{k,t,min}$ is the minimum allowable output during the t period of the k power station (depending on the type and characteristics of the turbine); $N_{k,t,max}$ is the expected output of power station k at a certain head at time t.

(5) Reservoir discharge flow constraint

$$Q_{k,t,\mathrm{min}}\le Q_{k,t}\le Q_{k,t,\mathrm{max}} \tag{6}$$

where $Q_{k,min}$ and $Q_{k,max}$ are respectively the minimum and maximum discharge of the k reservoir during the t period.

(6) Initial water level constraint

$$Z_{\mathrm{k,1}}=Z_{k,0} \tag{7}$$

where $Z_{k,0}$ is the water level in the initial period of k reservoir.

2.3 Model Solution

The output of cascaded hydropower stations is intricate, influenced by inflow, regulation, operation mode, and turbine capacity. Water head is determined by reservoir levels and losses. The objective function is simplified for ease of calculation. The Danjiangkou Hydropower Station oversees a vast watershed. Daily discharge minimally affects upstream levels, considered fixed at typical monthly averages. Downstream levels are calculated using turbine discharge-water level curves. Utilizing 1969-2019 inflow and water level data, cascade regulation aims beyond max power, easily meeting ecological flow requirements. Dry season data serves as short-term dispatching benchmarks.

The solution of short-term optimal scheduling model is a typical target multi-stage decision. Considering that there is water stagnation time (3 hours) between Danjiangkou and WangFuzhou steps, and the objective function is nonlinear, the dimension of direct dynamic programming method is higher. When dealing with optimization problems under complex constraints, Progressive Optimality Algorithm (POA) is adopted to solve the model by iterative method.

Initialization sets initial and terminal water levels, an initial water level path, and decision variables with adjustable step sizes and accuracy targets. Iterative optimization involves fixing and optimizing water levels at select time steps, adjusting flows to maximize objectives (e.g., power generation), and repeating this process with adjacent steps. Iterative propagation continues this backward-forward adjustment until reaching predefined accuracy. Upon convergence, the algorithm outputs the optimized operational plan, encompassing reservoir levels, capacities, generation flows, and outputs.

2.4 Relationship between Ecological Requirements and Objective Function

Under ecological assessment constraints, the Danjiangkou Reservoir's water supply to the Han River's middle and lower reaches post-diversion must maintain a minimum flow of 490m^3/s. As hydraulic systems advanced, ecological assessment requirements evolved into three stages:

(1) Trial Operation Stage (B1)

An ecological assessment section was established at the Danjiangkou Reservoir's downstream outflow, mandating a 490m^3/s average flow. The reservoir ensured stable water supply to the Han River, while Wangfuzhou Reservoir sustained high-head power generation, discharging water based on inflow and maintaining normal high water levels. Both reservoirs aimed to maximize total cascade power generation.

(2) Short-term Operation Stage (B2)

Following years of operation, to reactivate Danjiangkou's peak shaving, the ecological assessment section was shifted to Wangfuzhou's downstream outflow in 2019, requiring a 490m^3/s average flow for Wangfuzhou. Danjiangkou's peak shaving capabilities fluctuated Wangfuzhou's water levels, reducing its generation. This stage balanced maximizing Danjiangkou's peak shaving and Wangfuzhou's power generation within the cascade.

(3) Long-term Operation Stage (B3)

With downstream hydropower development and river canalization, the ecological assessment remains at Wangfuzhou's downstream outflow, but shifts to a daily average flow of 490m³/s. Objectives align with the short-term stage. However, with grid integration of new energy sources, Danjiangkou may engage in hydropower-photovoltaic complementary scheduling, ceding daytime capacity to photovoltaics and peaking during evening loads, facilitating electricity transfer.

3 Analysis of Ecological Requirements Affect the Operation Mode of the Cascade Reservoir

3.1 Results of Cascade Reservoir Operation in Different Ecological Requirements

Given that Wangfuzhou Reservoir is a daily regulation reservoir, and the daily average discharge flow from the Danjiangkou Reservoir needs to reach 490m³/s, the operational boundaries for a typical day in February are taken as the calculation conditions. Specifically, the average operating water level of the Danjiangkou Reservoir is set at 159m, while the Wangfuzhou Reservoir starts and ends at its normal high water level (86.23m), maintaining a discharge flow of 490m³/s. To investigate the impact of different ecological assessment requirements in the lower reaches of the Han River on the joint operation of cascade reservoirs, optimization scheduling is conducted based on differentiated objective functions for the three stages. The summary of the calculation results is presented in Table 1.

Table 1. Summary of power generation indexes of cascade reservoirs under different optimization objectives

Optimization objective	Danjiangkou		Wangfuzhou		Total electricity / (10^4Kw·h)
	Max Output Variation /Mw	Daily electricity / (10^4Kw·h)	Max Output variation /Mw	Daily electricity / (10^4Kw·h)	
B1	0	694.29	0	93.17	787.46
B2	780	689.29	1.1	92.23	781.52
B3	780	689.29	6.82	92.28	781.57
B1-B2	-780	5.00	-1.1	0.94	5.94
B2-B3	0	0	-5.72	-0.05	-0.05

As can be seen from Table 1, the peak regulating capacity of Danjiangkou increased significantly in the recent operation stage compared with the trial operation stage, from no peak regulating capacity to 780Mw, indicating that Danjiangkou restored its original peak regulating capacity. However, the cascade power generation decreased by 59,400 kW·h, of which, Wang Fuzhou power generation decreased by 0.9400 kW·h. In the long-term operation stage, compared with the recent operation stage, when Danjiangkou restored the peak load capacity, the cascade power generation increased by 0.05

kW·h, mainly the additional power generation of Wang Fuzhou, indicating that the power generation efficiency of Wang Fuzhou was fully released.

3.2 Results of Cascade Reservoir Typical-Day Operation in Different Ecological Requirements

Based on the analysis presented in the table and the subsequent discussion, the following insights can be gained regarding the impact of different ecological assessment requirements on the joint operation of cascade reservoirs in the Han River basin:

(1) Trial Operation Stage:

During Trial Operation, Danjiangkou Reservoir functioned as a run-of-river, adhering to ecological flow requirements, limiting storage use and regulatory functions. Wangfuzhou Reservoir similarly operated without significant regulation, both maintaining a stable 490m³/s downstream flow.

(2) Short-term Operation Stage:

In the Short-term Stage, with revised ecological requirements, the cascade aimed for differentiated power generation. Danjiangkou regained peak shaving, actively regulating the grid. Fig. 2 depicts fluctuations in its water level and discharge, up to 1380m³/s daily, impacting output by 780MW. Wangfuzhou counter-regulated, pre-releasing water for storage space, adjusting downstream flow twice daily to maintain 490m³/s, though with a daily power loss of 0.94 million kWh compared to Trial Operation.

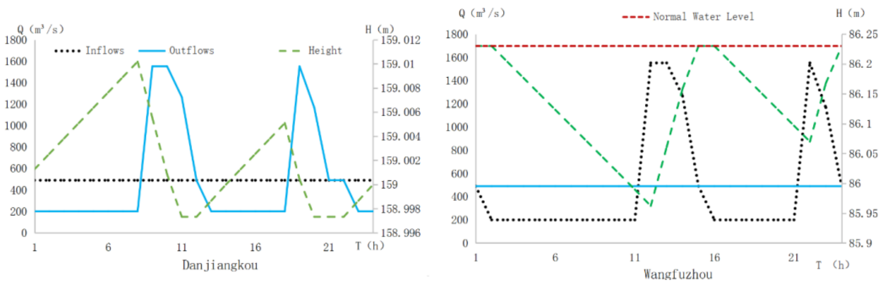

Fig. 2. Short-term operation stage daily process of cascade reservoir

(3) Long-term Operation Stage:

In the long-term stage, the ecological assessment requirement shifted to focusing solely on the average daily discharge flow of 490m³/s from the Wangfuzhou Power Plant.

The Danjiangkou Reservoir continued to operate similarly to the short-term stage, engaging in peak shaving activities as needed.

The Wangfuzhou Reservoir, aiming to maximize its power generation efficiency, adjusted its water discharge to closely match the ecological assessment requirement, maintaining a relatively stable flow of approximately 490m³/s throughout the day. This allowed the Wangfuzhou Power Plant to operate more efficiently, contributing to a slight increase in overall cascade power generation compared to the short-term stage.

In summary, the different ecological assessment requirements significantly influenced the operational strategies of the cascade reservoirs. The transition from a strictly regulated flow regime to one that prioritized peak shaving capabilities and then to a balance between ecological and economic objectives highlights the need for flexible and adaptive management approaches in multi-purpose reservoir systems.

3.3 Analysis of the Maximum Control Water Level on the Operation of Wangfuzhou Reservoir

Based on the analysis provided in the question, the impact of different maximum operating water levels for the Wangfuzhou Reservoir during low water periods, with allowances for temporary overfilling of 10cm to 20cm, has been evaluated. The results, as summarized in Table 2 and illustrated in Figures 3 and 4, offer valuable insights into the operational trade-offs.

Table 2. The power generation of Wangfuzhou Hydropower Station at different maximum operating control water levels

Boundary Conditions	Trial Operation	No Overfilling	10cm Overfilling	20cm Overfilling
Electricity / (10^4Kw·h)	93.17	92.23	93.14	93.40
Duration of $Z>Z_{normal}$ /(h)	0	0	13	15

Key Findings:

(1) No Overfilling Scenario:

When the Wangfuzhou Reservoir does not overfill, it generates 0.95 million kWh less electricity compared to the trial operation stage where it did not participate in peak shaving. This reduction is attributed to the need to maintain stable downstream flows while accommodating Danjiangkou's peak shaving activities.

(2) 10cm Overfilling Scenario:

With a 10cm overfill allowance, the Wangfuzhou Reservoir's power generation increases by 0.92 million kWh, nearly matching the trial operation stage's output, with only a 0.03 million kWh deficit. This improvement is due to the expanded storage capacity available for counter-regulation during Danjiangkou's peak shaving periods. The high water level persists for 13 hours, indicating a manageable increase in storage duration.

(3) 20cm Overfilling Scenario:

Allowing a 20cm overfill results in a daily power generation increase of 1.18 million kWh, exceeding the trial operation stage by 0.23 million kWh. However, the high water level persists for 15 hours, slightly longer than the 10cm overfill scenario. This increased storage duration, while beneficial for power generation, also poses a higher flood risk.

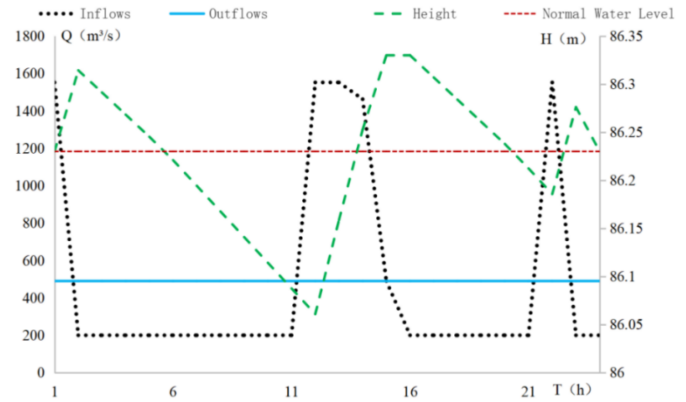

Fig. 3. Operation process of Wangfuzhou reservoir under the condition of 10cm overfilling scenario

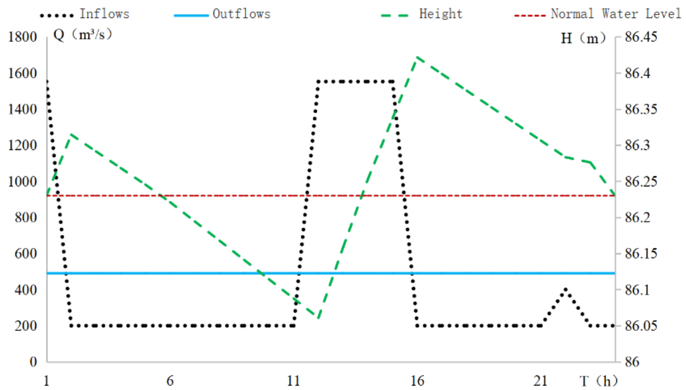

Fig. 4. Operation process of Wangfuzhou reservoir under the condition of 20cm overfilling scenario

Based on the analysis, selecting a maximum operating control water level with a 10cm overfill allowance for the Wangfuzhou Reservoir appears to be the most favorable option. It effectively restores Danjiangkou's peak shaving capability while compensating for the power generation loss at Wangfuzhou. Additionally, the duration of high water levels is relatively short, minimizing potential flood risks.

4 Conclusion and Prospect

An analysis of the results of differentiated dispatching targets for typical low-water days of cascade reservoirs leads to the following conclusions: When the ecological assessment section is set downstream of the Wangfuzhou Reservoir, the original peak shaving capacity of the Danjiangkou Hydropower Plant is restored, but there is a loss in total daily power generation. When the average water supply flow rate for the Wangfuzhou Power Plant is required to be $490m^3/s$, the daily power generation loss of the Wangfuzhou Power Plant is approximately 1% during the coordination with the peak shaving process of the Danjiangkou Power Plant. When the ecological assessment requirement is changed to a daily average water supply flow rate of $490m^3/s$ for the Wangfuzhou Power Plant, the power generation efficiency of the Wangfuzhou Reservoir is unleashed, resulting in an increase of approximately 5,000 kWh in daily power generation.

When the Danjiangkou Reservoir participates in peak shaving and the Wangfuzhou Reservoir is allowed to temporarily overfill by 10cm to 20cm, the daily power generation increases significantly compared to the normal high-water-level operation of the Wangfuzhou Reservoir, compensating for the power loss due to the restoration of peak shaving capacity at Danjiangkou. However, it is essential to note that the overfilling of the Wangfuzhou Reservoir increases the safety risks to the dam, necessitating more detailed research and risk-based decision-making.

China's wind and photovoltaic power generation commenced development around 2010 and has since experienced rapid growth. Since 2016, the annual newly-added capacity of wind and photovoltaic power has surpassed that of thermal power. Under the dual-carbon targets, the substitution of renewable green energy for thermal power as the primary component of power supply represents the future development trajectory of power systems. Hubei Province, situated in central China, experiences more than half of the days in the hottest July and August as sunny, with total solar radiation accounting for 25% of the annual total, indicating abundant solar energy resources. The restoration of peak shaving capacity at the Danjiangkou Wangfuzhou Power Station can collaborate with photovoltaic power stations to effectively utilize solar energy resources in central China, significantly alleviating the tension of power supply during peak periods in July and August. Integrating the development of hydropower stations with the installation of new energy sources such as photovoltaic and wind power, and constructing an integrated wind-photovoltaic-hydro-storage system holds significant importance for realizing supply-side structural reform in the power system, further facilitating the achievement of dual-carbon targets [18].

The restoration of peak shaving capacity at the Danjiangkou Reservoir provides conditions for cascade power plants to participate in the complementary use of intermittent energy sources such as wind, solar, and hydropower. Further research can be conducted by combining the different economic benefits of peak and off-peak power generation.

Acknowledgments

National Key Research and Development Program of China 2022YFC3005504

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