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Multi-Objective Synergetic Operation for Cascade Reservoirs in the Upper Yellow River

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Abstract: The Yellow River, a critical water resource, faces challenges stemming from increasing water demand, which has led to detrimental effects on hydropower generation and ecological balance. This paper will address the complex task of balancing the interests of hydropower generation, water supply, and ecology within the context of cascade reservoirs, specifically Longyangxia and Liujiaxia reservoirs. Employing a systemic coupling coordination approach, we constructed a multi-objective synergetic model of the upper Yellow River in order to explore synergies and competitions among multiple objectives. The results reveal that there is a weak competitive relationship between hydropower generation and water supply, a strong synergy between hydropower generation and ecology, and a strong competitive relationship between water supply and ecology. The Pareto solution set analysis indicates a considerable percentage (59%, 20%, and 8% in wet, normal, and dry years, respectively) exhibiting excellent coordination. The probability of excellent coordination decreases with diminishing inflow. The optimization scheme with the highest coupling coordination demonstrates significant improvements in power generation, water supply, and ecological benefits in the upper Yellow River without compromising other objectives, fostering the sustainable operation of hydropower generation, water supply, and ecology in the upper Yellow River.

Keywords: Yellow River Basin; multi-objective evolutionary algorithm; cascade reservoirs; coupling

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1. Introduction

The rapid development of urbanization and industrial expansion has exacerbated the scarcity of water, presenting a formidable challenge that profoundly impacts the sustainable advancement of regions [1]. The rational allocation of water resources not only conserves water but also substantially augments its efficiency [2]. Traditional reservoir operations primarily focus on flood control and hydropower generation [3,4], frequently neglecting concerns pertaining to riverine ecology and water supply. Current demands on reservoir operation necessitate a higher standard—simultaneously addressing traditional functions while considering riverine ecology, reservoir operation, and downstream agricultural and industrial water needs [5]. The Yellow River is currently grappling with severe ecological and water resource challenges [6]. By the end of 2018, the total population in the Yellow River Basin reached 420 million, accounting for 30.3% of China's population, while the Yellow River only accounts for 2.7% of China's freshwater resources [7]. On the other hand, the rapid socio-economic development in the Yellow River Basin has led to a continuous increase in the demand for water resources. Excessive water diversion has resulted in a reduction in ecological flow, causing a significant impact on the ecological balance of the Yellow River Basin. Increasing the discharge from upstream reservoirs inevitably compromises the hydropower generation efficiency of reservoirs, and the objectives of hydropower generation, water supply, and ecological flow have not found a balance in the Yellow River Basin, constraining high-quality development in this area [8,9]. The main facilities for the basin-wide regulation of water and sediment within the Yellow River are large multi-purpose reservoirs [10–12], such as the Longyangxia (LYX) and Liujiaxia (LJX) reservoirs. Since the joint operation of the LYX and LJX reservoirs, reductions in water discharge have resulted in continuous sedimentation and the narrowing of the Ningmeng River channel. This phenomenon has adversely affected the ecological environment of the Ningmeng River segment by diminishing the area of fish habitat and ecological flow [13,14]. Addressing this issue and implementing scientifically informed reservoir operations will promote the coordinated development of multiple objectives in the Yellow River Basin. Against the background of water scarcity, ensuring a balance between hydropower generation, irrigation, flood control, and ecological goals has become a focal point for scholars.

The multi-objective operation of cascade reservoirs is a complex task that typically involves multiple conflicting objectives, numerous decision variables, and uncertainties [15,16]. The multi-objective evolutionary algorithm (MOEA) has been considered an efficient way to address multi-objective problems. The recently popular MOEA based on group search has demonstrated excellent practical advantages in finding Pareto optimal solutions for high-dimensional decision variables and multiple nonlinear objective functions [17,18]. MOEA is an approach that simulates intergenerational natural selection and biological evolution to achieve global optimization. According to the various selection mechanisms, MOEAs can be broadly categorized into three groups: Pareto dominance-based MOEA [19,20], indicator-based MOEA [21], and decomposition-based MOEA. The MOEA based on decomposition with a differential evolution operator (MOEA/D [22]) is considered one of the most efficient algorithms, especially for solving complex multi-objective problems. Therefore, we made a considerable effort to successfully establish a multi-objective model for LYX and LJX reservoirs based on MOEA/D.

In the study of multi-objective reservoir operation, Olofintoye [23] successfully combined artificial neural networks with multi-objective differential evolution algorithms, applying them to the inflow forecasting and real-time multi-objective optimization scheduling of the Vanderkloof Reservoir in South Africa. This integration significantly improved the multi-objective scheduling capacity of the reservoir. Liu [24] employed a sliding support vector to derive optimal operation for spillways. These rules were integrated into the multi-objective optimization scheduling for flood control and hydropower generation at the Three Gorges Reservoir. The findings underscored the pronounced influence of varying sequences and quantities of spillway usage on the multi-objective benefits of the reservoir. Afshar [25] introduced a hybrid automated and coordinated search method that decomposes the operation of cascade reservoirs into subproblems involving the optimization operation of a number of smaller-scale reservoirs. The result indicates an improvement in the operational efficiency of cascade reservoirs using this method. Wang [26] introduced the concept of subjective weighting rate, coupled with ecological risk, to present an optimal decision-making method. This approach was employed in the decision-making process for the multi-objective optimal operation of ecology and hydropower generation at the Three Gorges Reservoir. Uen [27] focused on the synergistic optimization of water, food, and energy relationships and established a multi-objective optimal model for the Taiwan Shimen Reservoir. The model targeted the maximization of hydropower generation and reservoir storage. The NSGA-II algorithm was applied for the solution, leading to satisfactory results. Zhang [28] proposed an improved multi-objective firefly algorithm to solve a multi-objective optimal model for cascade reservoirs, considering power generation, ecology, and navigation. The algorithm achieved good convergence and a well-distributed Pareto solution set.

The multi-objective reservoir operation models mentioned above, which aim to maximize overall benefits such as hydropower generation, minimize water supply shortage rates, or maximize reservoir sediment removal, may inadvertently compromise the interests of specific critical objectives. Implementing a total basin benefit-oriented operation strategy might lead to substantial ecological or socio-economic losses, particularly in river systems with intense competition among multiple objectives, such as the Yellow River, characterized by low water availability and high sediment load. Therefore, reservoir operation strategies should prioritize the fundamental guarantees of each objective, fostering synergistic development among multiple objectives rather than pursuing the maximization of specific benefits. Cooperative theory, as a scientific framework for studying scientific research on the transition from chaos to order, has found application in various fields of water resources management. Chang [29] proposed a reservoir multi-objective operation method based on cooperative theory, achieving favorable optimization results. Chang [30] successfully applied the theory to optimize objectives related to hydropower generation, water supply, and flood control in the Yellow River. Despite the rapid development of multi-objective reservoir optimization operations based on cooperative theory, achieving satisfactory results in the cooperative operation of multi-objective reservoirs still remains challenging. Research in the field of multi-objective cooperative operation has struggled to meet the requirements of coordinating the interests of multiple stakeholders effectively.

This paper focuses on the LYX and LJX reservoirs of the upper Yellow River Basin in view of the issue of balancing hydropower generation, water supply, and ecological flow caused by the reduction in water discharge after the construction of the two reservoirs. We developed a multi-objective model based on MOEA/D for the upper Yellow River to study the synergistic and competitive relationships among hydropower generation, water supply, and ecological flow under different hydrological scenarios for the LYX and LJX reservoirs. In order to address the challenges of achieving coordinated operation among multiple objectives in the upper Yellow River, we integrated a system coupling coordination model to construct an evaluation system for the coupled coordination of hydropower generation, water supply, and ecological flow in the upper reach of the Yellow River and established a new method for a multi-objective cooperative operation of cascade reservoirs based on the principles of systemic coupling coordination. By employing flexible constraint selection and adaptive adjustment of weight coefficients, the proposed approach aims to achieve sustainable and coordinated development among hydropower generation, water supply, and ecology in the upper Yellow River. This method contributes to filling existing research gaps in this field.

2. Study Area and Data

2.1. Study Areas

The Yellow River, which is also known as "China's Mother River" [31], is the second-longest river in China. Originating from the Ba Yan Har Mountains in the western Qinghai province, it traverses through nine provinces, covering a total length of 5463 km and boasting a basin area of 795,000 km^2, ultimately flowing into the Bohai Sea [32]. Known for its low water volume and high sediment content, the Yellow River stands as one of the world's renowned sediment-laden rivers, with an annual sediment transport of approximately 1.5×10^8 tons and an average annual discharge of 2.2×10^{10} m^3 [33]. Segmented into upper, middle, and lower reaches based on regional natural environments and hydrological conditions, the upper reach of the Yellow River spans from its source to Togtoh County in Inner Mongolia. This segment spans 3472 km, with a drop of 3494 m and a basin area of 428,000 km^2, constituting 53.8% of the entire Yellow River Basin. Its annual discharge accounts for over 60% of the total Yellow River Basin [34–36], making it a crucial water source region for the Yellow River Basin.

The LYX, a multi-year operation reservoir, and LJX, an annual operation reservoir (Figure 1), are situated in the upper Yellow River, controlling over 40% of the natural runoff of the Yellow River. These reservoirs hold critical significance as control hubs in the Yellow River Basin. The main characteristics of the cascade reservoirs, including water levels and power station parameters, are outlined in Table 1. The segment from the LYX reservoir to Lanzhou features numerous gorges and concentrated drops, offering abundant hydropower resources. The stretch from Lanzhou to the Toudaoguai River passes through the Ningmeng Plain, characterized by a wide valley in a desert region, with complex variations in the water–sediment relationship and drastic changes in river morphology. The construction of upstream dams has led to a reduction in inflow to the Ningmeng River segment, aggravated by a high-sediment load, causing severe sedimentation and the formation of a new suspended riverbed and thus posing significant threats to flood control and ecology [37,38]. Therefore, the rational operation of the LYX and LJX reservoirs holds paramount significance for hydropower generation, water supply, and ecological preservation in the upper Yellow River. The general intention is displayed in Figure 2.

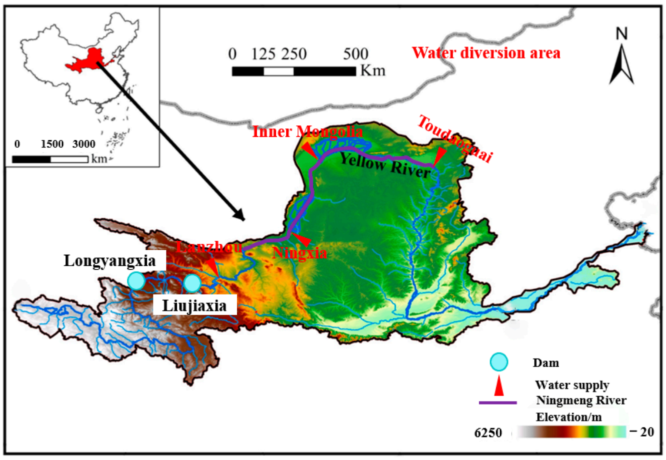


Figure 1. Diagram of study area.

Table 1. The characteristics of Longyangxia and Liujiaxia reservoirs.

Characteristics	Longyangxia	Liujiaxia
Normal water level (m)	2600	1735
Flood limit water level (m)	2594	1726
Dead water level (m)	2560	1694
Total storage (10^8 m^3)	247	57
Power generation capacity (MW)	128	139

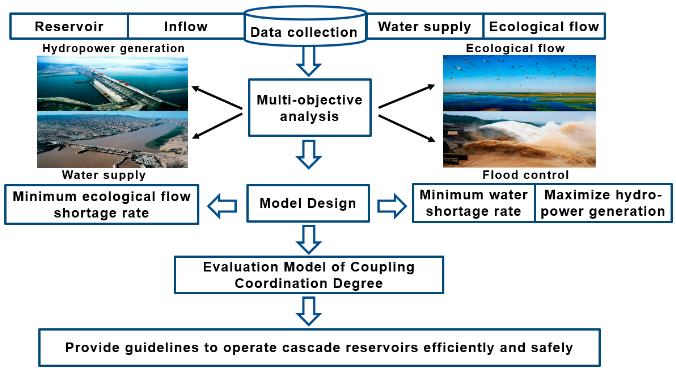


Figure 2. Research flowchart.

2.2. Data Sources

The LYX and LJX reservoirs regulate the water supply of agriculture, crucial urban centers of the upper Yellow River region, as depicted in the monthly water supply chart for the upper Yellow River segment (Figure 3). The upper Yellow River region encompasses two major irrigation areas: the Ningxia Irrigation Area and the Inner Mongolia Irrigation Area. These areas cover an expansive 6573 km^2 and 21,300 km^2, respectively. About 80% of the water that is diverted is used for irrigation, constituting the primary source of water for regional economic activities. Key crops for agricultural irrigation in the upper Yellow River include rice, wheat, maize, and others, with peak irrigation demands concentrated in the periods from April to July and September to November [39].

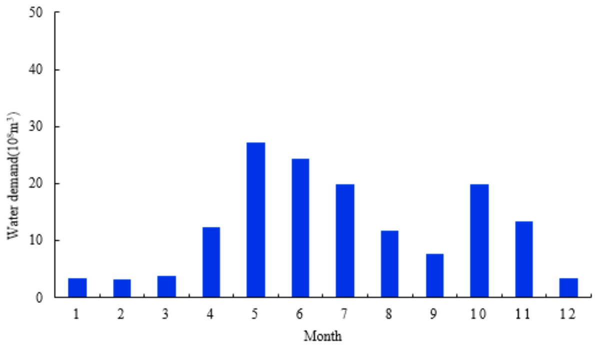


Figure 3. Monthly water demand in the upper Yellow River.

In recent years, watershed managers have shown significant concern for ecological issues because the ecological flow assurance rate is too low. Since the operation of the LYX and LJX reservoirs, there has been a notable alteration in the natural flow conditions of the upper Yellow River. Annual runoff at hydrological stations such as Xiaochuan, Xiaheyan, and Toudaoguai has seen a reduction ranging from 20% to 40%. Furthermore, the peak runoff has shifted from June to May and October, leading to channel contraction and a decrease in fish habitats, among other ecological challenges. As the TouDaoGuai Hydrological Station is strategically located at the juncture of the upper and middle reaches of the Yellow River, serving as a crucial monitoring point for the main stream, in this study, it was designated as the ecological flow control station for the upper Yellow River. In order to accurately calculate ecological flow, we digitized a large number of datasets from the Toudaoguai Hydrological Station and the LYX and LJX reservoirs from 1954 to 2018 and utilized the monthly average flow data from the Toudaoguai Hydrological Station for the period 1954 to 1968 (before the construction of the LYX and LJX reservoirs) as a baseline (Figure 4). Based on Tennant's method [40,41], the ecological flow of the river channel was calculated. Given that the period from April to June represents the peak spawning season for fish in the upper Yellow River, it is suitable to set the ecological flow during this time at 50% of the multi-year average monthly runoff. For the months of January to March and July to December, the ecological flow was set at 35% of the multi-year average monthly runoff. Taking into consideration the water demand in the middle and lower reaches of the Yellow River and referring to the "Comprehensive Planning of the Yellow River Basin (2012–2030)" [42], its ecological flow was determined. Addressing the challenge of channel contraction and diminishing fish habitats in the upper Yellow River, Hu [43] analyzed the water–sediment interaction of the Yellow River. The results suggest that maintaining a flow rate of 1000–2000 m^3/s during the flood season in July can prevent further channel contraction. In this study, three scenarios for ecological flow during the flood season in July were considered: 2000, 1500, and 1000 m^3/s. The adjustment duration was set at 31 days to prevent further degradation of the river's ecology. The suitable ecological flow for this river segment is summarized in Table 2.

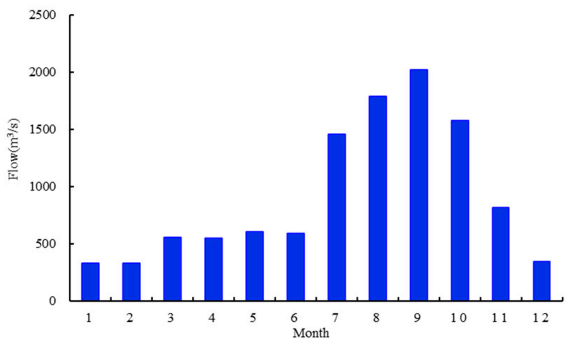


Figure 4. The natural flow of Toudaoguai Hydrological Station (1954–1968).

Table 2. Monthly flow rates required to sustain the ecology Unit:m^3/s.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Appropriate ecological flow	250	250	250	275	303	295	1000–2000	625	706	552	286	250

3. Methods

3.1. Multi-Objective Framework

Given the rapid pace of societal advancement, reservoirs are required to fulfill flood control tasks while meeting the demands for energy and water supply [44,45]. LYX-LJX cascades, serving as key regulatory hubs, undertake the mission of comprehensive resource utilization. Therefore, this paper identifies hydroelectric power generation, water supply, and ecology as primary objectives.

3.1.1. Hydropower Generation

Hydropower generation stands as a critical function of the reservoir and constitutes one of the primary research objectives of this study, shown as follows:

$$maxF = \sum_{i=1}^{N} \sum_{t=1}^{T} k_i * q_{i,t} * h_{i,t} * \tau_t \tag{1}$$

where F is the total hydropower generation in one year (kW·h), k_i represents the output coefficient specific to the ith hydropower, $q_{i,t}$ is the average discharge of the ith reservoir in the tth month (m^3/s), $h_{i,t}$ is the average water level of the ith reservoir in the tth month (m), τ_t is the time interval (month), N is the number of reservoirs, and T is the number of operation periods (T = 12).

3.1.2. Water Supply

To assess the water supply case, minimizing the water supply shortage rate was established as the criterion for evaluating water supply.

$$minS = \begin{cases} \sum_{t=1}^{T} \sum_{i=1}^{N} \frac{Rd_t - Rt_t}{Rd_t}, if Rt_t < Rd_t \\ 0, if Rt_t \geq Rd_d \end{cases} \tag{2}$$

where S represents the water shortage rate in one year, and Rt_t and Rd_t denote the water supply and water demand for the ith reservoir in the tth month (m^3).

3.1.3. Ecological Flow

To alleviate the adverse impacts on riverine ecology caused by the operation of cascade reservoirs, the minimum shortage rate of ecological flow was adopted as the criterion for ecological assessment. By adjusting reservoir discharge, efforts were made to minimize instances of insufficient ecological flow.

$$minE = \begin{cases} \sum_{t=1}^{T} \sum_{i=1}^{N} \frac{EF_t - E_t}{EF_t}, if E_t < EF_t \\ 0, if E_t \geq EF_t \end{cases} \quad (3)$$

where E is the ecological flow shortage rate in one year, while EF_t and E_t represent, respectively, the demand for ecological flow and the actual ecological flow in the tth month (m^3/s).

3.1.4. Constraints

(1) Water balance constraints

$$V_{i,t+1} = V_{i,t} + (Q_{i,in,t} - Q_{i,out,t}) * \tau_t \quad (4)$$

where $V_{i,t}$ and $V_{i,t+1}$ represent the ith reservoir storages at tth and $(t+1)$th, respectively. $Q_{i,in,t}$ and $Q_{i,out,t}$ represent the ith Reservoir's average inflow and average outflow in the tth month (m^3/s).

(2) Water release capacity constraints

$$Q_{i,t}^{min} \leq Q_{i,t} \leq Q_{i,t}^{max} \quad (5)$$

where $Q_{i,t}^{min}$ and $Q_{i,t}^{max}$ represent the minimum and maximum discharge in the tth month (m^3/s).

(3) Power generation output constraints

$$q_{i,t}^{min} \leq q_{i,t} \leq q_{i,t}^{max} \quad (6)$$

where $q_{i,t}^{min}$ and $q_{i,t}^{max}$ denote the minimum and maximum hydraulic turbine discharge in the tth month (m^3/s).

(4) Water-level constraints

$$Z_{i,t}^{min} \leq Z_{i,t} \leq Z_{i,t}^{max} \quad (7)$$

where $Z_{i,t}^{min}$ and $Z_{i,t}^{max}$ represent the minimum and maximum water levels in the tth month, respectively.

3.2. Spearman Correlation Coefficient

In statistics, the method of correlation analysis is primarily employed to quantify the degree of correlation between two variables and subsequently assess the relationship between them [46]. It is defined as the Pearson correlation coefficient for ordinal variables [47]. The Spearman correlation analysis method was utilized to calculate the mutual relationships among multiple objectives of the upper Yellow River, explicitly delineating synergistic or competitive associations among these objectives.

$$r_{xy} = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)} \quad (8)$$

where r_{xy} is the Spearman rank correlation coefficient between variables x and y with values in the range of [−1, 1], d_i is the rank differences for each pair of observations, and n is the sample size. When $r_{xy} > 0$, the two variables are positively correlated; conversely, when $r_{xy} < 0$, they are negatively correlated. When $r_{xy} = 0$, variables x and y are considered uncorrelated.

3.3. Evaluation Model of Coupling Coordination Degree

Coupling denotes the coordinated interaction of two or more systems [48]. The degree of coupling coordination serves as an indicator of the level of coordination in development and evolution, uncovering the trend from discoordination to ordered coordination. We introduced a coupling coordination model [49] to analyze the results of the multi-objective synergetic model of the LYX and LJX reservoirs that evaluates coupling coordination relationships among multiple objectives as follows:

$$D = \sqrt{CT} \tag{9}$$

$$C = \frac{3 * \sqrt[3]{U_1 U_2 U_3}}{U_1 + U_2 + U_3} \tag{10}$$

$$T = \alpha_1 U_1 + \alpha_2 U_2 + \alpha_3 U_3 \tag{11}$$

where D represents the degree of coupling coordination; C represents the coupling's degree; and T is the coordination degree, which is a comprehensive evaluation index of the coordination of the hydropower generation, water supply, and ecological objectives. U_1, U_2, and U_3 represent the development indexes of the hydropower generation objective, water supply objective, and ecological objective; α_1, α_2, and α_3 are the weights assigned to the three objectives, respectively, reflecting the varying emphasis placed on each objective by decision-makers. The calculated values of D were categorized into the following grade intervals, serving as the foundation for assessing the degree of coupling coordination based on which LYX-LJX cascades operated, as illustrated in Table 3.

Table 3. Classification of the degree of coupling coordination.

C value interval	[0, 0.1]	(0.1, 0.2]	(0.2, 0.3]	(0.3, 0.4]	(0.4, 0.5]
Coupling type	Severely Imbalanced	Significantly Imbalanced	Moderately Imbalanced	Slightly Imbalanced	Approaching Imbalance
C value interval	(0.5, 0.6]	(0.6, 0.7]	(0.7, 0.8]	(0.8, 0.9]	(0.9, 1.0]
Coupling type	Barely Coordinated	Elementary Coordination	Intermediate Coordination	Good Coordination	Excellent Coordination

4. Results and Discussion

4.1. Analyzing Competition among Multiple Objectives

Three distinct hydrological years were selected as trigger points for the model: the wet year (2018), the normal year (2013), and the dry year (2016). As the study area does not involve special locations, laws, or regional conditions, the three objectives were weighted at 1/3. The MOEA/D was utilized to address the multi-objective question of the LYX and LJX reservoirs, generating a random population of 500 and iterating 2000. Applying the Spearman method, we computed the correlation coefficients between hydropower generation, water supply, and ecological flow in each typical year (Table 4). The results indicate a consistent trend in the correlation relationships between hydropower generation, water supply, and ecological flow for the selected years. The correlation coefficient between power generation and water supply of LYX and LJX reservoirs is negative, with a relatively small absolute value, suggesting a weak competitive relationship between these two objectives. The positive correlation coefficient between power generation and ecology indicates a strong synergy between these objectives. The negative correlation coefficient between ecology and water supply reveals a pronounced competitive relationship between these two objectives. The variation in correlation coefficients between different objectives in the three typical years underscores the significant impact of upstream water inflow on the relationships between objectives. In particular, in the dry year, the competition between water supply and ecological flow becomes more pronounced as a result of the limited upstream inflow.

Table 4. Monthly flow rates demand for inner-river ecology.

Typical Year	Correlation Coefficients		
	Hydropower Generation and Water Supply	Hydropower Generation and Ecology	Water Supply and Ecology
Wet year	−0.307	0.865	−0.514
Normal year	−0.246	0.920	−0.450
Dry year	−0.161	0.639	−0.808

4.2. The Coupling Coordination Type of the Upper Yellow River

Employing models of the LYX and LJX reservoirs based on the MOEA/D, the Pareto solution set was computed, and a coupled coordination model was employed for multi-objective decision-making. Firstly, the dimensionless processing of the set was carried out, with the development index for each objective (m = 1, 2, and 3) representing the calculated values of the objective function. Next, the coupling degree and coordination degree among hydropower generation, water supply, and ecology were calculated, with each subsystem assigned an equal weight of 1/3. Finally, the coupling coordination degrees for the typical years were computed. The distribution of coupling coordination levels is illustrated in Figure 5; the greater the degree of coupling coordination in the operation scheme, the higher the level of synergy observed among power generation, water supply, and ecology. When the coupling coordination degree is less than 0.5, it indicates an imbalance among hydropower generation, water supply, and ecology, with one or more objectives falling significantly below the normal standards, leading to significant economic or ecological losses in the upper Yellow River Basin. From Figure 5, it can be observed that the operations of intermediate coordination ($0.7 < D \leq 0.8$), good coordination ($0.8 < D \leq 0.9$), and excellent coordination ($0.9 < D \leq 1.0$) comprise the majority in the wet, normal, and dry years. These indicate that the overall coordination among the objectives of power generation, water supply, and ecology in the LYX-LJX cascades is relatively high. However, there still exists a certain level of competition among multiple objectives. The proportion of solutions in the Pareto set with excellent coordination ($D > 0.9$) is 59%, 20%, and 8% for wet, normal, and dry years, respectively. This indicates that during the wet year, operation for the LYX-LJX cascades is more likely to achieve excellent coordination, resulting in greater overall benefits in hydropower generation, water supply, and ecology. For normal and dry years, more stringent requirements are needed for coordination among multiple objectives for the LYX-LJX cascades. Moreover, the high-quality coordination in the upstream Yellow River is significantly influenced by the upstream inflow; the greater the upstream inflow, the higher the probability of excellent coordination in the joint operation scheme for the LYX-LJX cascades. The reason is that the water supply and ecological flow in the upper Yellow River come from the outflow of LYX-LJX cascades from the perspective of basin management.

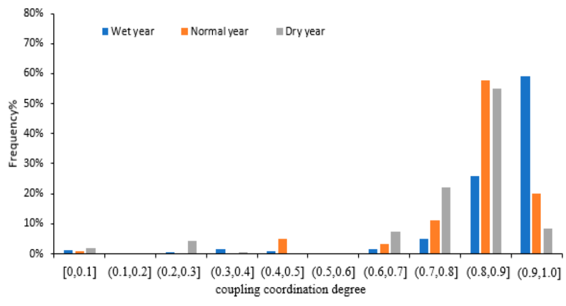
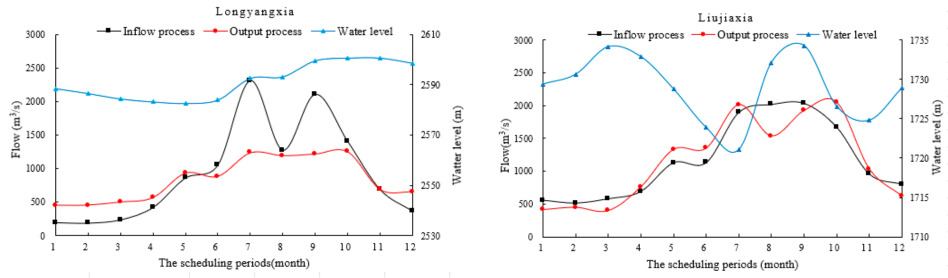


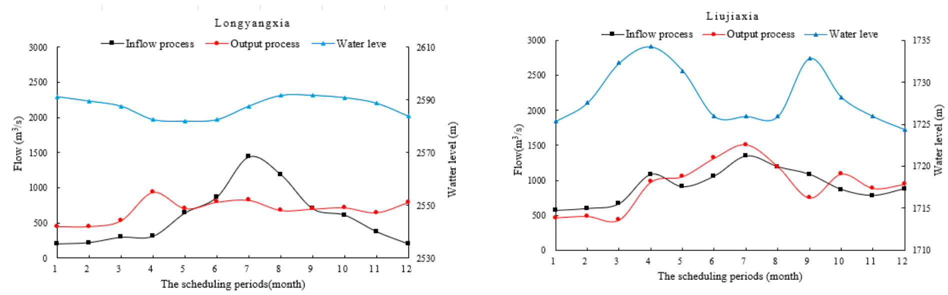
Figure 5. Distribution of coupling coordination degrees of Pareto scheme set.

4.3. Optimal Operation of the Upper Yellow River

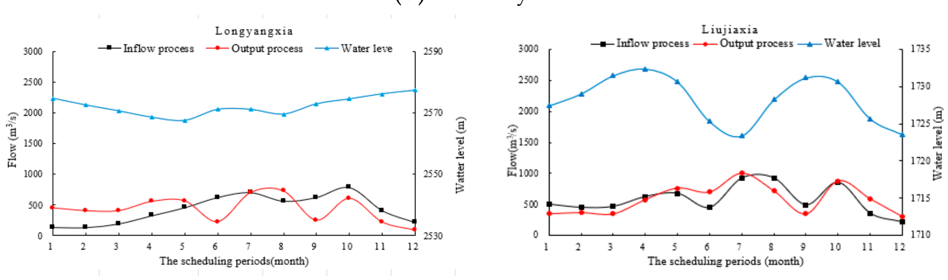
In this study, we selected the scheme with the highest coupling coordination as the optimal scheme for the multi-objective operation of the reservoirs. The maximum coupling coordination for the wet, normal, and dry years is 0.93, 0.92, and 0.91, respectively. The optimization process for the optimal scheme is illustrated in Figure 6. Comparing the existing and optimized target values for wet, normal, and dry years (Table 5), it is observed that in wet and normal years, the operation with the highest coupling coordination tends to improve hydropower generation benefits compared to the existing operation, while in dry years, it tends to enhance the benefits of water supply and ecology. Hydropower generation increases by 8.41 billion kWh, 5.76 billion kWh, and 0.41 billion kWh for wet, normal, and dry years, respectively. The water supply shortage rate and ecological flow shortage rate exhibit significant improvement compared to the existing operations. This improvement is attributed to the fact that water demand in the upper Yellow River is mainly concentrated in the spring (April to June) and winter (October to November) irrigation periods, mostly outside the flood season. Simultaneously, the ecological flow demand is primarily concentrated from July to October. The optimization scheme for the LYX and LJX reservoirs, while adhering to reservoir safety scheduling rules, increases the flood peak regulation rate during the flood season, resulting in increased reservoir storage capacity. The LYX reservoir increases the outflow in the ice-flood control period, which leads to a corresponding increase in hydropower generation. Simultaneously, the outflow of LYX is stored in the LJX reservoir, preventing the wastage of water resources and further enhancing water resource utilization efficiency.



(**a**) Wet year



(**b**) Normal year



(**c**) Dry year

Figure 6. The operation processes of LYX-LJX cascades during the typical years.

Table 5. Optimization results of the joint operation model.

Scheme	Typical Year	Hydropower Generation (10^8 kW·h)	Water Shortage Rate of Water Supply	Ecological Water Shortage Rate
Actual scheme	Wet year	152.42	2.38%	2.99%
	Normal year	134	5.87%	5.01%
	Dry year	82.61	15.31%	20.24%
Optimization scheme	Wet year	160.83	0.78%	1.50%
	Normal year	139.76	1.34%	2.04%
	Dry year	83.02	5.68%	9.30%

In general, as the upstream water inflow decreases, the hydropower generation of the LYX and LJX reservoirs decreases, and the water supply and ecological shortage rates increase, leading to a decrease in the overall benefits of the Yellow River Basin. However, the benefits of the optimization scheme consistently exceed the existing values. The optimal operation indicates that, based on the coupling coordination degree evaluation method, the multi-objective coordinated model of the upper Yellow River can effectively enhance the benefits of water supply and ecology in normal and dry years without compromising hydropower generation benefits. In the wet year, there is a significant improvement in the benefits of hydropower generation, water supply, and ecology.

5. Conclusions

This article introduces an innovative method for the multi-objective coordinated regulation of the LYX and LJX reservoirs based on the principles of systemic coupling coordination. Through the development of a multi-objective synergetic model, we explored the synergistic or competitive relationships among the objectives of the LYX and LJX reservoirs, aiming to effectively manage conflicts among hydropower generation, water supply, and ecology.

(1) Using the Spearman method, the results indicate that the correlation coefficients for hydropower generation and water supply objectives during the wet, normal, and dry years were −0.307, −0.246, and −0.161, respectively, indicating a weak competitive relationship between the two objectives. Conversely, during the wet, normal, and dry years, the correlation coefficients for hydropower generation and ecological objectives were 0.865, 0.920, and 0.639, respectively, indicating a strong synergistic relationship between the two objectives. Furthermore, for water supply and ecological objectives during the wet, normal, and dry years, correlation coefficients were −0.514, −0.450, and −0.808, respectively, indicating a strong competitive relationship between the two objectives.

(2) The results of the multi-objective synergetic model for the LYX and LJX reservoirs indicate that among Pareto solution sets for typical years, the proportion of schemes exhibiting excellent coordination ($D > 0.9$) was 59%, 20%, and 8%, respectively. This indicates that the LYX and LJX reservoirs are more likely to operate with a high degree of cooperation during wet years. In contrast, achieving a high degree of coordination between multiple objectives in normal and dry years imposes stricter requirements on reservoir operation. Additionally, the excellent coordination among multiple objectives in the upper Yellow River increases with the augmentation of upstream inflow, indicating that the benefits of cascade reservoirs also increase. From a basin management standpoint, it is prudent to discard schemes characterized by low coupling coordination in order to reconcile conflicts of interest among various departments and foster the harmonized development of the basin system.

(3) The scheme with the highest level of coupled coordination was selected as the optimization scheme of the multi-objective coordinated model of the LYX and LJX reservoirs. The findings reveal that optimization schemes exhibit a tendency to en-

hance hydropower generation benefits compared to the existing operation in wet and normal years. In the dry year, there is a tendency to improve both the benefits of water supply and ecology. Hydropower generation increases by 88.41×10^8, 5.76×10^8, and 0.41×10^8 kW·h in the wet, normal, and dry years, respectively. Furthermore, there is a substantial improvement in the water supply shortage rate and the ecological flow shortage rate compared to the existing operation.

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