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Coordinated Operation and Compensation Allocation for Sustainable Reservoir-System Management in the Yellow River Basin

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Abstract

Sustainable reservoir-system management requires coordinated operation to balance economic benefits, sediment regulation, and ecological requirements while maintaining equitable and durable cooperation among participating reservoirs. Focusing on the Wanjiazhai, Sanmenxia, and Xiaolangdi reservoirs in the middle and lower Yellow River Basin, this study develops an integrated framework that links multi-objective reservoir operation, coordination-oriented scheme selection, and compensation allocation under representative dry, normal, and wet hydrological conditions. NSGA-II is used to identify Pareto trade-offs among sediment transport, electricity production, and ecological water-deficit control, while the coupling-coordination degree model is applied to select schemes with balanced overall performance. CRITIC-TOPSIS is then used to allocate compensation by integrating static engineering attributes with operation-induced dynamic responses. The results show that the maximum coupling-coordination degrees reach 0.81, 0.88, and 0.90 under dry, normal, and wet conditions, respectively. Compared with actual operation, the recommended schemes increase total electricity production while reflecting hydrologically dependent trade-offs in sediment transport and ecological water-deficit control. Xiaolangdi Reservoir consistently receives the largest compensation share, followed by Wanjiazhai Reservoir and Sanmenxia Reservoir, and this ranking remains consistent across alternative allocation methods. By linking operational trade-offs with reservoir-specific contributions and compensation priorities, the framework supports more adaptive and equitable joint operation and provides a quantitative decision-support approach for improving the long-term environmental, economic, and institutional sustainability of reservoir-system management in the Yellow River Basin.

Keywords: sustainable reservoir management; coordinated reservoir-system operation; compensation allocation; multi-objective optimization; Yellow River Basin

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1. Introduction

The Yellow River Basin faces pronounced conflicts in water-resource allocation due to limited water availability, complex water–sediment dynamics, and increasingly stringent ecological constraints [1–3]. Uneven spatiotemporal precipitation patterns, substantial interannual variability in runoff, and complex sediment-transport processes further intensify competition among water supply, sediment regulation, ecological protection, and socioeconomic development [4]. Under the strategic framework of ecological protection and high-quality development in the Yellow River Basin, reservoir operation has increasingly shifted from pursuing individual engineering objectives, such as water supply, flood control, and electricity production, toward balancing sediment regulation, energy supply, the provision of minimum ecological discharge, and regional development needs [5,6]. Reservoir systems provide critical infrastructure for achieving these objectives because upstream–downstream hydraulic connectivity, storage capacity, and differentiated reservoir functions enable multiple operational objectives to be coordinated within an integrated system [7–9]. Such coordinated operation not only affects system-level performance but also redistributes the regulatory responsibilities, benefits, and operational burdens among individual reservoirs. Consequently, quantifying reservoir-specific contributions to coordinated operation and establishing corresponding compensation mechanisms are essential for sustaining effective reservoir-system coordination.

At the theoretical level, coordinated reservoir-system operation and compensation-benefit allocation are closely interconnected because both aim to improve system-level performance while reconciling the interests of participating reservoirs. Synergetics theory emphasizes that the overall performance of a complex system depends on the coupling relationships and degree of coordination among its constituent elements [10]. For reservoir systems, operational performance therefore depends on the coordination of multiple functions rather than on the simple aggregation of benefits generated independently by individual reservoirs [11,12]. Water-resource value theory further suggests that coordinated regulation alters the spatiotemporal allocation and functional use of water resources, thereby influencing the realization and distribution of their economic, social, and ecological values [13]. From the perspective of externality theory, individual reservoirs may assume additional regulatory responsibilities, incur opportunity costs, or make operational adjustments to support system-wide objectives, while part of the resulting benefits may accrue to other reservoirs or regions within the system [14,15]. The principles of Pareto improvement and interest coordination therefore require system-wide operational gains to be aligned with the contributions and costs of individual reservoirs [16,17]. Collectively, these theoretical perspectives provide a basis for jointly examining reservoir-operation optimization, reservoir-specific contributions, and compensation-benefit allocation within a unified analytical framework.

Existing studies on reservoir-system operation can generally be grouped into two closely related strands, namely multi-objective operation optimization and compensation-benefit allocation. Early research on reservoir operation primarily focused on individual reservoirs or small cascade systems, with optimization objectives centered on electricity production, flood control, and water supply. Dynamic programming, linear programming, and nonlinear programming were commonly adopted to derive operating rules and identify optimal release or storage decisions under prescribed engineering constraints [18–20]. As reservoir systems increasingly assumed multiple basin-management functions, research expanded from single-reservoir, single-objective operation toward multi-reservoir, multi-objective coordination. Electricity production, water-supply security, flood-risk reduction, sediment regulation, and the provision of minimum ecological discharge have consequently been incorporated into integrated multi-objective optimization frameworks [21–23]. To address the nonlinear relationships and competing objectives inherent in such systems, evolutionary optimization methods, including genetic algorithms, particle swarm optimization, differential evolution, and NSGA-II, have been widely employed. These methods enable the generation of Pareto-optimal solution sets and provide a quantitative basis for characterizing trade-offs among competing operational objectives, thereby facilitating the comparison of alternative reservoir-system operation schemes under different management priorities.

Research on compensation-benefit allocation has developed in parallel with the growing emphasis on coordinated reservoir operation. Existing studies mainly address the identification of benefits generated by coordinated operation, the sharing of associated costs, and the allocation of gains among participating reservoirs or stakeholders [24,25]. Early allocation approaches commonly relied on individual engineering or benefit-related indicators, such as installed capacity, guaranteed output, effective storage capacity, and long-term average electricity production, to characterize the relative contribution of each reservoir. As coordinated reservoir systems have become more complex, compensation analysis has increasingly incorporated multi-indicator evaluation methods to capture differences in engineering characteristics, regulatory capacity, and benefit contributions across reservoirs. Representative approaches include comprehensive evaluation methods, squared-deviation methods, the Shapley value, and TOPSIS-based approaches [26]. These approaches provide a methodological basis for synthesizing multidimensional information on reservoir characteristics and contributions into comparable allocation weights, thereby supporting the determination of compensation shares under coordinated operation.

Accordingly, the contribution of this study lies in establishing an integrated optimization–evaluation–allocation framework that connects multi-objective reservoir operation, coordination-oriented scheme selection, and reservoir-specific compensation allocation within a unified analytical process. From the perspective of sustainable reservoir-system management, the framework addresses not only the operational trade-offs among sediment transport, electricity production, and ecological water-deficit control, but also the distribution of regulatory responsibilities and benefits among participating reservoirs. First, water-release and sediment-transport benefits, electricity production, and ecological water deficits are incorporated into a multi-objective operation model, and NSGA-II is used to characterize the Pareto trade-off space under representative dry-, normal-, and wet-year conditions. The coupling-coordination degree model is subsequently introduced as a post-optimization evaluation criterion to distinguish among Pareto solutions according to their overall coordination performance, thereby extending conventional Pareto-based analysis from the generation of non-dominated solutions to the selection of a coordination-oriented operating scheme. Second, the selected operation scheme is directly linked to compensation allocation through an indicator system that integrates static engineering attributes with operation-induced dynamic responses. In addition to long-term average electricity production, installed capacity, effective storage capacity, and guaranteed output, the indicator system incorporates variations in electricity production, water level, and release discharge to characterize the actual operational adjustments undertaken by individual reservoirs under different hydrological conditions. CRITIC-TOPSIS is then applied to synthesize these multidimensional indicators and determine the corresponding reservoir-specific compensation shares. By linking system-level operating performance with reservoir-specific contributions and compensation priorities, the framework provides a quantitative basis for improving the environmental, economic, and institutional sustainability of coordinated reservoir management.

The aim of this study is to develop an integrated framework for sustainable reservoir-system management in the Wanjiazhai–Sanmenxia–Xiaolangdi reservoir system. Specifically, the study examines trade-offs among sediment transport, electricity production, and ecological water deficits under representative hydrological conditions, identifies operation schemes with relatively balanced performance, and evaluates the differentiated contributions of individual reservoirs to coordinated operation. The resulting compensation allocation is further compared with alternative allocation methods to assess the consistency of reservoir contribution patterns. Through this integrated analysis, the study seeks to support adaptive reservoir operation, more equitable compensation allocation, and the long-term viability of coordinated reservoir-system management in the Yellow River Basin.

2. Materials and Methods

2.1. Study Area and Data Sources

This study focuses on the Wanjiazhai–Sanmenxia–Xiaolangdi reservoir system in the Yellow River Basin. The Yellow River Basin is characterized by uneven spatiotemporal distribution of water resources and pronounced interannual runoff variability. The middle and lower reaches have long faced multiple constraints, including insufficient inflow, sediment deposition, flood-control safety and ecological-discharge requirements, which create strong trade-offs and coordination relationships among reservoir operation objectives. Wanjiazhai, Sanmenxia and Xiaolangdi reservoirs are arranged in cascade along the main stem of the Yellow River and constitute an important engineering system for water-sediment regulation and water-resource allocation in the middle and lower Yellow River Basin. Wanjiazhai Reservoir mainly supports water supply, flood control, and electricity production. Sanmenxia Reservoir regulates inflow and sediment-transport processes in the middle reaches. Xiaolangdi Reservoir serves as a key control node for downstream flood control, sediment-deposition mitigation, water-sediment regulation, and ecological operation. The three reservoirs form a spatial cascade connection and exhibit functional complementarity. Their joint operation directly affects water-discharge and sediment-transport processes, electricity-production benefits, and the provision of minimum ecological discharge in the middle and lower Yellow River Basin (Figure 1).

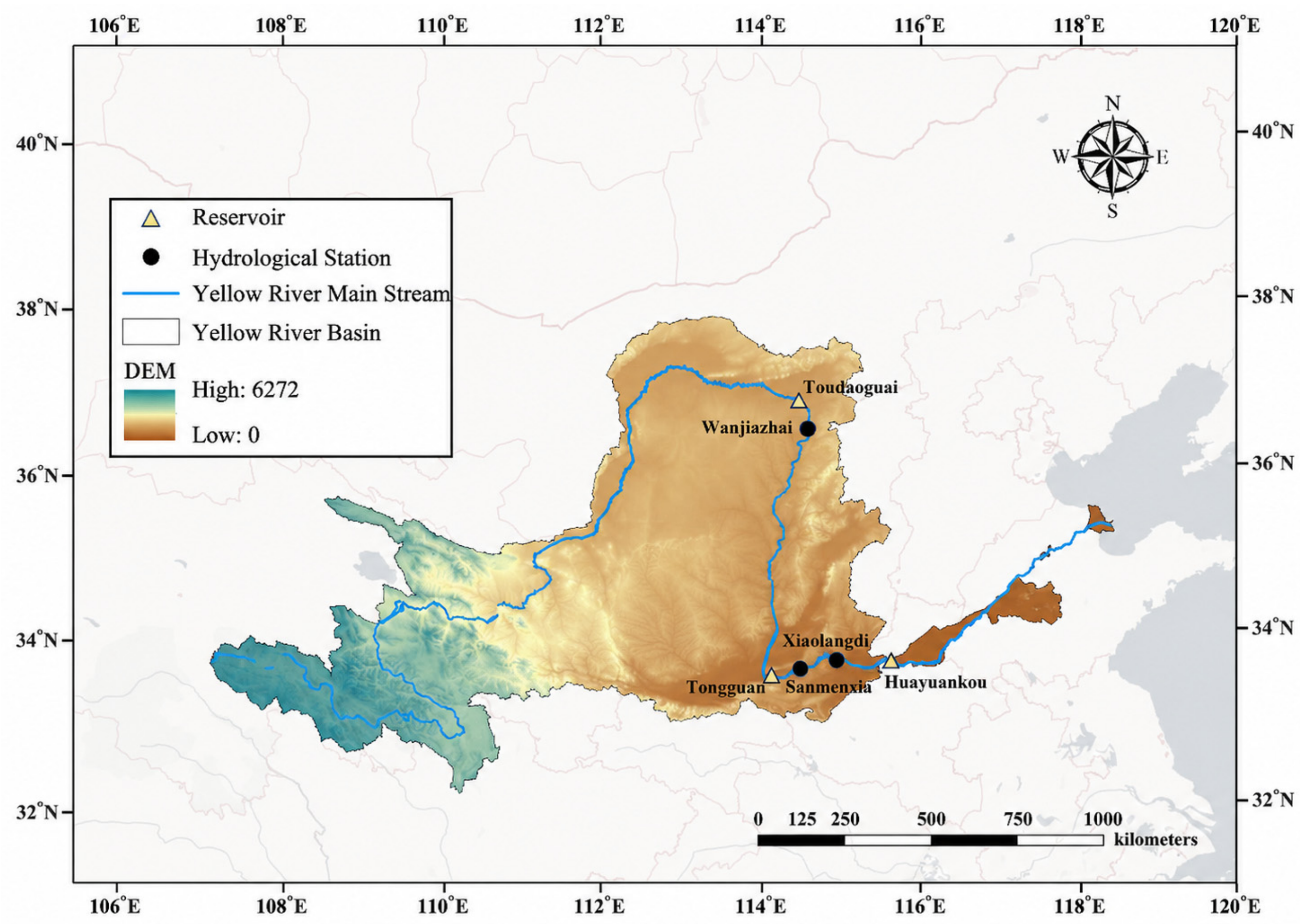

Figure 1. Location of the Wanjiazhai–Sanmenxia–Xiaolangdi reservoir system in the Yellow River Basin.

The data used in this study comprise reservoir engineering parameters, hydrological and sediment records, ecological water-demand data, and reservoir operation records. Reservoir engineering parameters include design hydraulic head, dead water level, flood-limited water level, normal storage level, total storage capacity, effective storage capacity, installed capacity, guaranteed output, power-output coefficient, long-term average electricity production, and maximum turbine discharge (Table 1). These parameters were compiled from reservoir operation and management records and were used to define the physical and engineering constraints of the optimization model, calculate electricity-production benefits, and construct the static indicators for compensation allocation.

Table 1. Main characteristic parameters of the reservoir system in the middle and lower Yellow River Basin.

Reservoir	Wanjiazhai	Sanmenxia	Xiaolangdi
Design hydraulic head (m)	81.2	30	112
Dead water level (m a.s.l.)	952	300	230
Flood-limited water level (m a.s.l.)	966	305	248
Normal storage level (m a.s.l.)	977	318	275
Total storage capacity (hm^3)	900	4688	12,650
Effective storage capacity (hm^3)	445	439	5100
Installed capacity (MW)	1080	250	1800
Guaranteed output (MW)	185	113	354
Power-output coefficient/$kW \cdot s \cdot m^{-4}$	8.4	8.4	8.3
Average electricity production (GWh)	2750	1000	5100
Maximum turbine discharge ($m^3\ s^{-1}$)	1800	1559	1800

Hydrological and sediment data were collected from the Hydrological Yearbook of the People's Republic of China for the Yellow River Basin. Records from the Tongguan and Huayuankou hydrological stations were used to characterize runoff and sediment conditions in the middle and lower Yellow River Basin. The data include runoff volume, sediment transport load, sediment concentration, discharge, and sediment-transport rate. In this study, sediment transport load refers to the amount of sediment conveyed by the flowing water over the specified period and should not be interpreted as sediment deposition or accumulation within reservoir storage. Based on the relative runoff conditions recorded at the two stations, 2010, 2012, and 2018 were selected as representative dry, normal, and wet years, respectively (Table 2). Monthly inflow and sediment records for the corresponding years were organized according to the monthly time step adopted in the reservoir-operation model.

Table 2. Runoff and sediment-transport data for the middle and lower Yellow River Basin.

Year	Hydrological Station	Annual Runoff Volume (km^3)	Annual Sediment Transport Load (Mt)	Annual Mean Sediment Concentration (kg m^{-3})	Annual Mean Discharge ($m^3\ s^{-1}$)	Annual Mean Sediment Transport Rate (t s^{-1})
2010	Tongguan Station	26.25	227	8.64762	832.382	7.198123
2010	Huayuankou Station	27.63	124	4.48788	876.1416	3.932014
2012	Tongguan Station	35.14	206	5.86227	1114.1416	6.532217
2012	Huayuankou Station	38.80	138	3.55670	1230.34	4.375951
2018	Tongguan Station	41.46	373	8.99662	1314.688	11.82775
2018	Huayuankou Station	44.80	344	7.67857	1420.599	10.90817

Ecological water-demand data were obtained from publicly available materials issued by the Yellow River Conservancy Commission and represent ecological-discharge requirements at key control sections in the middle and lower Yellow River Basin. The Huayuankou section was used as the downstream ecological-control section, with monthly minimum and suitable ecological-discharge requirements summarized in Table 3. These values were used as reference thresholds for calculating ecological water deficits under alternative operation schemes. Reservoir water levels, reservoir releases, electricity production, and other operational information used for comparison between actual and optimized operation and for constructing the dynamic compensation indicators were obtained from reservoir operation management records.

Table 3. Ecological discharge requirements at key sections of the middle and lower Yellow River during critical periods ($m^3\ s^{-1}$).

Month	Huayuankou Section	
	Minimum Ecological Discharge	Suitable Ecological Discharge
January	200	400
February	200	400
March	200	400
April	200	800
May	200	800
June	200	800
July	200	800
August	200	800
September	200	800
October	200	800
November	200	400
December	200	400

Before model implementation, the datasets from different sources were organized using a consistent monthly time step and checked for consistency in units, temporal correspondence, and physically reasonable ranges. Engineering parameters were converted to the units required by the model, while hydrological, sediment, ecological-discharge, and reservoir-operation records were matched according to the corresponding reservoir, hydrological station, and operation period. No statistical smoothing or artificial interpolation was applied to alter the observed hydrological and sediment characteristics of the representative years. The resulting datasets were subsequently used as deterministic inputs to the optimization and compensation-allocation models.

Several sources of uncertainty should nevertheless be recognized. Hydrological and sediment observations may contain measurement and reporting errors, particularly because sediment conditions can vary substantially within a month, and annual or monthly records cannot fully represent short-term water-sediment fluctuations. Reservoir operation records may likewise be affected by differences in monitoring and record-keeping procedures. In addition, the ecological-discharge requirements adopted in this study represent prescribed reference conditions rather than direct observations of ecosystem response and therefore involve uncertainty associated with the definition of suitable ecological demand. Because these inputs are treated deterministically in the present model, such uncertainties may influence the calculated objective values and the exact numerical compensation shares. The analysis therefore places greater emphasis on the relative trade-offs among operation objectives and the comparative compensation patterns across representative hydrological conditions than on interpreting individual numerical results as uncertainty-free estimates.

2.2. Coordinated Operation Model for the Reservoir Systems

2.2.1. Objective Functions

Coordinated reservoir-system operation aims to integrate multiple functional demands, including water release, sediment transport, electricity production and ecological discharge requirements, thereby improving overall system performance under water-resource constraints and competing operational objectives [27–29]. The Yellow River Basin is characterized by water scarcity, complex water–sediment processes and substantial pressure on meeting ecological-discharge requirements. Single-objective operation is therefore insufficient to capture the multiple demands of reservoir-system operation and reveal trade-offs among competing objectives [30,31]. To balance objective representativeness, model parsimony and result interpretability, sediment-transport benefit maximization, total electricity-production maximization and ecological water-deficit minimization are selected as the three core optimization objectives. These objectives characterize the water-release and sediment-transport, electricity-production and ecological-discharge dimensions of reservoir-system operation, respectively.

(1) Sediment-Transport Benefit Maximization Objective

The middle and lower reaches of the Yellow River are characterized by high sediment concentrations [32,33]. Reservoir-system operation should therefore satisfy conventional storage–release and flood-control safety requirements while enhancing riverine sediment-transport capacity through appropriate regulation of reservoir releases, thereby mitigating the adverse effects of sediment deposition on channel flood-conveyance capacity and effective reservoir storage [34–36]. The sediment-transport benefit of a reservoir system reflects the amount of sediment conveyed with reservoir releases and its contribution to maintaining downstream sediment-transport processes over the operation horizon. The present model does not explicitly simulate the erosion, flushing or removal of coarse sediment already deposited within reservoir storage. Instead, the sediment objective is evaluated using the sediment concentration and sediment-carrying discharge associated with the modeled release process. Accordingly, this study uses reservoir-system sediment-transport benefit maximization as the sediment-transport objective of reservoir-system operation, as expressed in Equation (1).

$$\max Y_1 = \sum_{i=1}^{N} \sum_{t=1}^{T} Q_{i,t}^{S} W_{i,t} \Delta t \tag{1}$$

where $\max Y_1$ denotes the maximization of the sediment-transport benefit of the reservoir system. N is the total number of reservoirs. T is the total number of operation periods. $Q_{i,t}^{s}$ denotes the generation discharge of reservoir i during period t. $W_{i,t}$ denotes the hydraulic head for electricity production of reservoir i during period t. Δt denotes the duration of the operation period.

(2) Electricity-Production Maximization Objective

Electricity production constitutes an important economic function of the reservoir system [37,38]. The amount of electricity produced is jointly determined by turbine discharge, hydraulic head and operation duration and therefore reflects the utilization of available hydropower resources during coordinated reservoir-system operation [39]. Optimizing reservoir water levels and reservoir-release processes can improve electricity-production performance while satisfying flood-control, sediment-transport and ecological-discharge requirements [40,41]. Accordingly, this study uses total electricity-production maximization as the economic objective of reservoir-system operation, as expressed in Equation (2).

$$max Y_2 = \sum_{t=1}^{T} \sum_{i=1}^{N} \delta K_i Q_{i,t}^{e} \Delta H_{i,t} \Delta t \tag{2}$$

where $\max Y_2$ denotes the maximization of electricity-production benefit. δ is the on-grid electricity tariff. K_i is the power-output coefficient of reservoir i. $Q_{i,t}^{e}$ denotes the generation discharge of reservoir i during period t. $\Delta H_{i,t}$ denotes the hydraulic head for electricity production of reservoir i during period t. Δt denotes the duration of the operation period.

(3) Ecological Water-Deficit Minimization Objective

The ecological objective reflects the capacity of reservoir-system operation to meet downstream ecological-discharge requirements [42–44]. Through storage–release regulation, reservoir systems can adjust downstream releases to support ecological discharge during dry periods and moderate excessive flow fluctuations during wet periods, thereby reducing the adverse effects of hydrological variability on river ecosystems [45]. Ecological water deficit represents the shortfall between the actual ecological discharge and the prescribed suitable ecological discharge and is used to quantify the extent to which reservoir-system operation meets downstream ecological-discharge requirements [46]. Accordingly, this study uses ecological water-deficit minimization as the ecological objective of reservoir-system operation, as expressed in Equation (3).

$$minY_3 = \begin{cases} 0, & Q_{i,t}^E \geq D_{i,t}^E \\ \sum_{t=1}^{T}\sum_{i=1}^{N}\left(D_{i,t}^E - Q_{i,t}^E\right), & Q_{i,t}^E < D_{i,t}^E \end{cases} \quad (3)$$

where $minY_3$ denotes ecological water-deficit minimization. $D_{i,t}^E$ and $Q_{i,t}^E$ denote the prescribed suitable ecological discharge and the actual ecological discharge during period t, respectively.

2.2.2. Constraints

Coordinated reservoir-system operation must balance multiple objectives, including sediment-transport benefit maximization, total electricity-production maximization and ecological water-deficit minimization, while satisfying the basic physical and engineering safety constraints of reservoir operation [47–49]. Based on the practical requirements of reservoir-system operation, we specify water-balance constraints, reservoir water-level constraints, reservoir-release constraints, power-output constraints and non-negativity constraints.

The water-balance constraint describes changes in reservoir storage between adjacent operation periods and represents the most fundamental physical constraint in reservoir operation models. It is expressed as $U_{i,t+1} = U_{i,t} + (Q_{i,t} - q_{i,t} - I_{i,t})\Delta t$, where $U_{i,t}$ and $U_{i,t+1}$ denote the storage of reservoir i at the beginning of periods t and $t+1$, respectively. $Q_{i,t}$, $q_{i,t}$ and $I_{i,t}$ denote the inflow, controlled reservoir release and spill discharge of reservoir i during period t, respectively. Δt denotes the length of the operation period.

To ensure reservoir operation safety, the reservoir water level, reservoir release and power output of each reservoir must be controlled within their allowable ranges. These constraints are expressed as $\underline{Z_{i,t}} \leq Z_{i,t} \leq \overline{Z_{i,t}}$, $Q_{i,t}^{\min} \leq Q_{i,t} \leq Q_{i,t}^{\max}$ and $\underline{P_{i,t}} \leq P_{i,t} \leq \overline{P_{i,t}}$, respectively. In these expressions, $Z_{i,t}$, $Q_{i,t}$ and $P_{i,t}$ denote the operating water level, reservoir release and power output of reservoir i during period t, respectively. $Q_{i,t}^{\min}$ and $Q_{i,t}^{\max}$ denote the allowable minimum and maximum reservoir releases of reservoir i during period t, respectively. $\underline{P_{i,t}}$ and $\overline{P_{i,t}}$ denote the allowable minimum and maximum power outputs of reservoir i during period t, respectively. In addition, all variables in the above constraints are required to be non-negative to ensure their physical interpretability in reservoir operation.

2.2.3. Model Solution Using NSGA-II

Multi-objective optimization algorithms are designed to solve complex optimization problems involving multiple, often conflicting, objectives. They typically yield not a single optimal solution, but a set of mutually non-dominated Pareto-optimal solutions [50–52]. To handle trade-offs among objectives and ensure that operation schemes satisfy practical operational constraints, we apply the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to solve the coordinated reservoir-system operation model.

NSGA-II is a representative multi-objective evolutionary algorithm with robust global search capability and strong solution-diversity preservation [53]. The algorithm assigns Pareto dominance ranks through fast non-dominated sorting and uses crowding distance to measure the distribution of individuals within the same non-dominated front in the objective space, thereby balancing convergence and diversity of the solution set. NSGA-II also adopts an elitism strategy in which parent and offspring populations are combined, ranked and selected to reduce the risk of losing high-quality individuals during iteration. Compared with traditional weighted-sum methods, NSGA-II does not require predefined objective weights and can more fully characterize trade-offs and substitution relationships among operation objectives. It is therefore well suited to multi-objective, nonlinear and highly constrained optimal operation problems in reservoir systems.

During model solution, the monthly reservoir release, reservoir water level and storage of each reservoir are represented using real-valued decision variables. For each candidate solution, these variables are arranged according to reservoir and operation period to form a complete annual operating trajectory for the reservoir system. Each individual in the population therefore corresponds to one complete reservoir-system operation scheme. The initial population is generated within the prescribed operational ranges of the decision variables. Before objective evaluation and non-dominated sorting, each candidate scheme is checked against the physical and engineering constraints. Water-balance consistency is examined for each reservoir and operation period, while reservoir water levels, reservoir releases and power outputs are restricted to their allowable operating ranges. Schemes that do not satisfy the prescribed operational constraints are excluded from subsequent Pareto ranking and elite retention. For feasible individuals, the three objective-function values are calculated, after which fast non-dominated sorting and crowding-distance evaluation are performed. Offspring are generated through crossover and mutation, and the parent and offspring populations are combined for elitist selection. The procedure is repeated until the prescribed maximum number of generations is reached, yielding the Pareto solution set used for subsequent coordination-based scheme evaluation.

2.2.4. Operation Scheme Evaluation Based on the Coupling-Coordination Degree Model

The Pareto-optimal solution set obtained using NSGA-II contains multiple non-dominated operation schemes and reflects trade-offs among reservoir-system operation objectives. However, the solution set does not directly identify a single recommended scheme. To identify the recommended operation scheme from the perspective of overall coordination, we introduce a coupling-coordination degree model to evaluate the overall performance of each Pareto scheme across the sediment-transport, electricity-production and ecological-water-deficit dimensions [54,55].

Let U_1, U_2 and U_3 denote the standardized performance indices for sediment transport, electricity production and ecological water-deficit control, respectively. For each Pareto operation scheme, the objective-function values are first standardized, and the composite index of each objective dimension is then calculated using the corresponding indicator weights, as shown in Equation (4).

$$U_i = \sum_{j=1}^{m} \eta_{ij} F_{ij}, i = 1, 2, 3 \quad (4)$$

where U_i denotes the composite development index of subsystem i. F_{ij} denotes the standardized value of indicator j in subsystem i. η_{ij} denotes the corresponding indicator weight and satisfies the weight-normalization condition.

On this basis, the coupling degree, comprehensive coordination index and coupling-coordination degree are further calculated to evaluate the overall coordination level of each reservoir-system operation scheme, as expressed in Equations (5)–(7).

$$C = \frac{3\sqrt[3]{U_1 U_2 U_3}}{U_1 + U_2 + U_3} \tag{5}$$

$$T = \alpha_1 U_1 + \alpha_2 U_2 + \alpha_3 U_3 \tag{6}$$

$$D = \sqrt{CT} \tag{7}$$

where C denotes the coupling degree among the three objective dimensions. T denotes the comprehensive coordination index of the reservoir-system operation scheme. D denotes the coupling-coordination degree of the reservoir-system operation scheme. α_1, α_2 and α_3 are the weights of the three objective dimensions, and they satisfy $\alpha_1 + \alpha_2 + \alpha_3 = 1$. Equal weights are assigned to the three objective dimensions, with $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$. This setting is adopted because no explicit preference is assumed among the sediment-transport, electricity-production and ecological water-deficit dimensions, thereby avoiding subjective weighting and allowing the coupling-coordination degree to reflect their overall balance. In this study, the Pareto scheme with the highest D value is selected as the recommended operation scheme, representing the most balanced performance among sediment transport, electricity production and ecological water-deficit control within the examined Pareto solution set. The D values are divided into ten classification intervals (Table 4) to evaluate the coupling-coordination level of the reservoir system under coordinated operation.

Table 4. Classification criteria for the coupling-coordination degree.

Range	Coordination Level	Range	Coordination Level
[0,0.1)	Extreme disorder	[0.5,0.6)	Barely coordinated
[0.1,0.2)	Severe disorder	[0.6,0.7)	Primary coordination
[0.2,0.3)	Moderate disorder	[0.7,0.8)	Intermediate coordination
[0.3,0.4)	Mild disorder	[0.8,0.9)	Good coordination
[0.4,0.5)	Near disorder	[0.9,1]	High-quality coordination

2.3. Compensation Allocation Model for Coordinated Operation of the Reservoir Systems

2.3.1. Indicators for Compensation Allocation

Coordinated reservoir-system operation reshapes the operating processes of individual reservoirs, resulting in heterogeneous contributions and benefit variations in sediment transport, electricity production and ecological-discharge support. To characterize the basic support capacity, operational contribution and operational disturbance of each reservoir in coordinated operation, we construct a compensation-allocation indicator system from two dimensions, namely static characteristics and dynamic processes.

Static characteristic indicators primarily reflect the foundational role and potential contribution of reservoirs within the coordinated reservoir-system operation framework. Considering differences among reservoirs in engineering scale, storage-regulation capacity and electricity-production function, we select long-term average electricity production, installed capacity, effective storage capacity and guaranteed output as static characteristic indicators. Long-term average electricity production and installed capacity are used to characterize the electricity-production capacity of each reservoir and its contribution to the economic objective. Effective storage capacity reflects reservoir storage-regulation capacity and its supporting role in sediment regulation, flood-control operation and the provision of ecological discharge. Guaranteed output reflects the capacity of each reservoir to provide stable power output and therefore characterizes its long-term contribution to reliable electricity supply.

Dynamic process indicators primarily reflect benefit variations and operational disturbances associated with reservoir participation in coordinated operation. This study selects variation in electricity production, maximum water-level fluctuation rate and maximum reservoir-release fluctuation rate as dynamic process indicators. These indicators measure the effects of coordinated operation on electricity-production benefits, water-level dynamics and reservoir-release processes, respectively, as expressed in Equations (8)–(10).

$$\Delta W_i = W_i' - W_i \tag{8}$$

$$P_i = \frac{\left|\max_t |H'_{i,t+1} - H'_{i,t}| - \max_t |H_{i,t+1} - H_{i,t}|\right|}{\max_t |H_{i,t+1} - H_{i,t}|} \tag{9}$$

$$R_i = \frac{\left|\max_t |Q'_{i,t+1} - Q'_{i,t}| - \max_t |Q_{i,t+1} - Q_{i,t}|\right|}{\max_t |Q_{i,t+1} - Q_{i,t}|} \tag{10}$$

where ΔW_i, P_i and R_i denote the variation in electricity production, maximum water-level fluctuation rate and maximum reservoir-release fluctuation rate of reservoir i, respectively. W_i' and W_i denote the electricity production of reservoir i under coordinated operation and individual operation, respectively. $H'_{i,t}$ and $H_{i,t}$ denote the water level of reservoir i during period t under coordinated operation and individual operation, respectively. $Q'_{i,t}$ and $Q_{i,t}$ denote the release discharge of reservoir i during period t under coordinated operation and individual operation, respectively.

2.3.2. CRITIC-TOPSIS-Based Compensation Allocation Model

To improve the objectivity of compensation allocation for coordinated reservoir-system operation, this study constructs a CRITIC-TOPSIS compensation allocation model [56]. Let n denote the number of reservoirs participating in coordinated operation and m denote the number of compensation-allocation indicators. The original decision matrix $X = (x_{ij})_{n\times m}$ is constructed using the compensation-allocation indicators of each reservoir. To eliminate differences in measurement units and indicator directions, the original data are standardized to obtain the standardized matrix $X' = \left(x'_{ij}\right)_{n\times m}$.

For weight determination, the CRITIC method is used to account for both indicator variability and inter-indicator conflict. The information content and weight of indicator j are expressed as $C_j = \sigma_j R_j$ and $w_j = \frac{C_j}{\sum_{j=1}^{m} C_j}$, respectively. Here, $R_j = \sum_{k=1}^{m}\left(1 - r_{jk}\right)$. In these expressions, σ_j denotes the standard deviation of indicator j. r_{jk} denotes the correlation coefficient between indicators j and k. R_j denotes the conflict intensity between indicator j and the other indicators. w_j denotes the objective weight assigned to compensation-allocation indicator j.

To determine compensation allocation ratios, the TOPSIS method is used to evaluate the relative compensation score of each reservoir. The weighted standardized matrix $Y = (y_{ij})_{n\times m}$ is constructed using the CRITIC weights, and the positive and negative ideal solutions, Y^+ and Y^-, are then determined. The distances from reservoir i to the positive and negative ideal solutions are calculated as $D_i^+ = \sqrt{\sum_{j=1}^{m}(y_{ij} - Y_j^+)^2}$ and $D_i^- = \sqrt{\sum_{j=1}^{m}(y_{ij} - Y_j^-)^2}$, respectively. The relative closeness of reservoir i is then calculated as $S_i = \frac{D_i^-}{D_i^+ + D_i^-}$. Finally, the relative closeness values of all reservoirs are normalized to obtain the compensation allocation ratios, expressed as $\gamma_i = \frac{S_i}{\sum_{i=1}^{n} S_i}$. In this expression, γ_i denotes the proportion of compensation benefits allocated to reservoir i.

2.3.3. Comparative Allocation Methods

To provide a comparative reference for interpreting the CRITIC-TOPSIS compensation allocation results, the single-indicator method and the squared-deviation method are introduced as benchmark approaches. The single-indicator method determines compensation shares primarily according to individual engineering attributes, whereas the squared-deviation method integrates the allocation results obtained from different single-indicator approaches. The comparison is used to examine whether the relative allocation pattern identified by CRITIC-TOPSIS is consistent with that derived from alternative allocation principles, while differences in the resulting compensation shares are used to assess the influence of methodological choice on the allocation outcomes.

(1) Single-Indicator Method

The single-indicator method determines the compensation allocation share according to the proportion of a specific characteristic indicator of each reservoir relative to the total value across the reservoir system [57]. This study selects installed capacity, guaranteed output, long-term average electricity production and effective storage capacity as single-indicator allocation bases. These indicators reflect differences among Wanjiazhai, Sanmenxia and Xiaolangdi reservoirs in engineering scale, stable power-supply capacity, electricity-production potential and storage-regulation capacity. For a specific indicator, the compensation allocation ratio of reservoir i can be expressed as $\alpha_i = \frac{p_i}{\sum_{i=1}^{n} p_i}$. In this expression, α_i denotes the compensation allocation ratio of reservoir i, p_i denotes the value of the corresponding characteristic indicator for reservoir i and n denotes the number of reservoirs.

(2) Squared-Deviation Method

The squared-deviation method is used to generate an integrated allocation scheme based on the results obtained from single-indicator allocation methods [58]. This method determines weights by comparing the deviations of different single-indicator allocation results from the average allocation level. Assume that there are m single-indicator allocation schemes, and let x_iˆk denote the compensation allocation ratio of reservoir i under the k-th single-indicator allocation scheme. The average allocation ratio and variance for reservoir i are then calculated as $\bar{x}_i = \frac{1}{m}\sum_{k=1}^{m} x_i^k$ and $s_i^2 = \frac{1}{m-1}\sum_{k=1}^{m}(x_i^k - \bar{x}_i)^2$, respectively. The weight coefficient of reservoir i under the k-th allocation scheme is further calculated as $W_i^k = \frac{(m-1)s_i^2 - (x_i^k - \bar{x}_i)^2}{(m-1)s_i^2}$. After normalization, the corresponding weight is obtained as $\omega_i^k = \frac{W_i^k}{\sum_{k=1}^{m} W_i^k}$. Accordingly, the integrated compensation allocation ratio of reservoir i based on the squared-deviation method is calculated as $\beta_i = \sum_{k=1}^{m} \omega_i^k x_i^k$.

3. Results

3.1. Coordinated Operation Results Under Representative Hydrological Years

3.1.1. Pareto-Optimal Solution Sets Under Representative Hydrological Years

To characterize variations in coordinated reservoir-system operation under different inflow conditions, 2010, 2012 and 2018 are selected as representative dry, normal and wet years, respectively. The selection is based on the relative annual runoff levels observed at Tongguan and Huayuankou stations, where 2010 records the lowest runoff, 2012 an intermediate level, and 2018 the highest among the selected years. These contrasting runoff conditions provide a quantitative basis for comparing reservoir-system operation under relatively dry, normal and wet inflow scenarios. The operation model is then constructed with an annual horizon and a monthly time step. The model is implemented in MATLAB R2023a and solved using the NSGA-II algorithm. Candidate operation schemes are then evaluated for fitness and screened for feasibility under constraints related to water balance, water-level control, release discharge and power output. The algorithm parameters are set as follows: a population size of 300, a maximum of 500 iterations, a crossover distribution index of 20 and a mutation distribution index of 20. Non-dominated sorting and the crowding-distance mechanism are used to maintain the convergence and diversity of the solution set. The Pareto-optimal solution sets under dry-, normal- and wet-year scenarios are thereby obtained, providing a basis for subsequent operation-scheme selection and compensation-benefit allocation analysis. The distribution, continuity and spread of the Pareto solutions are further examined to provide additional evidence on the stability and interpretability of the identified trade-offs and to determine whether these trade-offs are supported by a sufficiently broad solution set rather than by isolated solutions.

Under the dry-year scenario, Table 5 shows that total electricity production ranges between 12,453 and 13,069 GWh, the sediment transport load ranges between 581 and 608 Mt, and the ecological water deficit ranges between 1047 and 3316 hm^3. These results indicate that, under relatively dry inflow conditions, reservoir-system operation schemes exhibit different combinations of electricity-production benefits, sediment-transport performance and ecological water-deficit control. Different non-dominated solutions correspond to distinct objective preferences, reflecting the trade-off characteristics of multi-objective operation. As shown in Figure 2a, the Pareto front under the dry-year scenario is generally smooth, indicating that the non-dominated solution set is continuous and well distributed in the objective space and can adequately reflect the substitution relationships among the three objectives. This distributional continuity provides additional evidence that the observed trade-offs are not driven by a small number of isolated solutions. The two-dimensional projection results further show an evident trade-off between electricity production and sediment transport load (Figure 2b–d). Operation schemes with higher electricity production generally correspond to lower sediment transport load. This suggests that, under water-supply constraints in dry years, operation strategies that place greater emphasis on electricity production tend to maintain the storage and hydraulic-head conditions favorable for power generation, thereby reducing the water available for concentrated reservoir releases that support sediment transport. As a result, the electricity-production objective and the sediment-transport objective exhibit a clear trade-off relationship.

Table 5. Pareto-optimal operation scheme sets for representative hydrological years.

	Dry Year			Normal Year			Wet Year		
Operation Scheme Set	Electricity Production (GWh)	Sediment Transport Load (Mt)	Ecological Water Deficit (hm^3)	Electricity Production (GWh)	Sediment Transport Load (Mt)	Ecological Water Deficit (hm^3)	Electricity Production (GWh)	Sediment Transport Load (Mt)	Ecological Water Deficit (hm^3)
1	12,720	601	2567	18,856	560	243	20,278	1100	41
2	12,453	608	1985	18,646	571	722	19,765	1177	394
3	12,790	600	2996	18,270	580	65	19,899	1169	0
…	…	…	…	…	…	…	…	…	…
298	12,831	596	2958	18,409	578	484	19,879	1171	839
299	12,818	599	3316	18,644	569	147	19,922	1169	546
300	13,069	581	1047	18,670	570	256	20,104	1159	791

Under the normal-year scenario, total electricity production ranges between 18,270 and 18,856 GWh, the sediment transport load ranges between 560 and 580 Mt, and the ecological water deficit ranges between 65 and 722 hm^3. Compared with the dry-year scenario, the normal-year scenario shows higher overall electricity production and a marked reduction in ecological water deficit. This indicates that improved inflow conditions provide greater operational flexibility for meeting downstream ecological-discharge requirements while supporting higher electricity production. As shown in Figure 2e, the Pareto front under the normal-year scenario remains relatively smooth, but the non-dominated solutions are more clustered in the objective space than those under the dry-year scenario and are mainly distributed in regions with lower ecological water deficit and relatively higher sediment transport load. This indicates that, when water-resource constraints are eased in normal years, coordinated reservoir-system operation can partly balance ecological-discharge requirements and sediment-transport demand, while the constraint imposed by the ecological water-deficit objective is reduced. The two-dimensional projection results further show that electricity production and sediment transport load still exhibit an evident trade-off relationship (Figure 2f–h). Schemes with higher electricity production generally correspond to lower sediment transport load. This suggests that, although water-resource conditions improve in normal years compared with dry years, the structural tension between storage conditions favorable for electricity production and reservoir-release requirements for sediment transport remains. Meanwhile, schemes with ecological water deficits close to zero are relatively concentrated, indicating that water availability in normal years can better support downstream ecological-discharge requirements. The main trade-off therefore shifts from a three-way competition involving ecological water-deficit control, electricity production and sediment transport toward a more pronounced trade-off between electricity production and sediment transport.

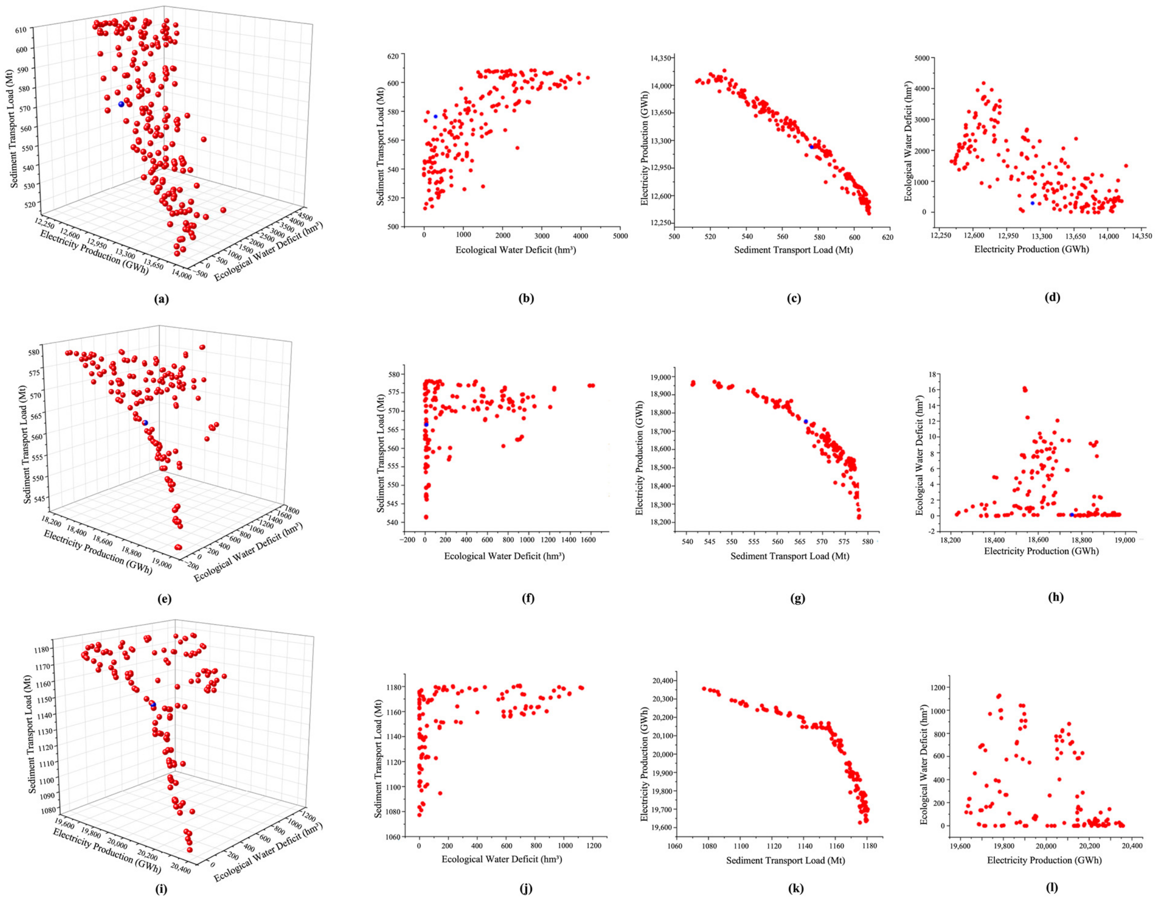

Figure 2. Pareto-optimal coordinated operation schemes under representative hydrological conditions. Panels (**a**), (**e**), and (**i**) show the three-dimensional Pareto fronts for the dry, normal, and wet years, respectively. Panels (**b**), (**f**), and (**j**) show sediment transport load versus ecological water deficit; panels (**c**), (**g**), and (**k**) show electricity production versus sediment transport load; and panels (**d**), (**h**), and (**l**) show ecological water deficit versus electricity production. Red points represent the Pareto-optimal solutions, while the blue points indicate the selected coordinated operation schemes for the corresponding hydrological conditions.

Under the wet-year scenario, total electricity production ranges between 19,765 and 20,278 GWh, the sediment transport load ranges between 1100 and 1177 Mt, and the ecological water deficit ranges between 0 and 839 hm^3. Compared with the dry-year and normal-year scenarios, the wet-year scenario shows increases in both electricity production and sediment transport load, with the increase in sediment transport load being more pronounced. This indicates that improved inflow and sediment conditions provide greater capacity for sediment transport while also supporting higher electricity production. Meanwhile, the ecological water deficit remains within a relatively low range, and some operation schemes achieve zero ecological water deficit, indicating that water availability in wet years can effectively support downstream ecological-discharge requirements. As shown in Figure 2i, the Pareto front under the wet-year scenario remains relatively smooth, and the non-dominated solutions are concentrated in the objective space, mainly in regions with low ecological water deficit. This suggests that, under relatively abundant water-resource conditions, the constraining effect of the ecological water-deficit objective on reservoir-system operation is weakened, and operation schemes are more strongly characterized by the trade-off between electricity production and sediment transport. The two-dimensional projection results further show that electricity production and sediment transport load still exhibit an evident trade-off relationship (Figure 2j–l). Schemes associated with higher sediment transport load generally correspond to lower electricity production. This indicates that, although wet years alleviate the overall water-resource constraint, the operational tension between maintaining storage conditions favorable for electricity production and providing concentrated reservoir releases for sediment transport remains unresolved.

3.1.2. Selection of the Optimal Operation Scheme

Based on the Pareto-optimal solution sets obtained for different representative hydrological years, a coupling-coordination degree model is further used to evaluate the overall coordination level of the non-dominated operation schemes and select the recommended scheme for each scenario. As shown in Figure 3, the distribution of coupling-coordination degrees across the Pareto solution sets provides additional information for evaluating the consistency of coordination performance under different hydrological conditions. Under the normal-year and wet-year scenarios, the coupling-coordination degrees of operation schemes are mainly concentrated in the [0.8, 0.9) interval, indicating an overall level of good coordination. Under the dry-year scenario, the coupling-coordination degrees are mainly distributed in the [0.7, 0.8) interval, corresponding to an intermediate coordination level. This result indicates that insufficient inflow intensifies water-resource allocation constraints and increases the difficulty of balancing sediment transport, electricity production and ecological water-deficit control. Meanwhile, a small number of low-coordination schemes are observed in all three representative hydrological years. This suggests that some Pareto non-dominated solutions may have relative advantages in a single objective or a partial combination of objectives, but their overall coordination level remains limited, making them unsuitable as comprehensive optimal operation schemes.

In terms of the optimal coordination level, the maximum coupling-coordination degrees under the dry-, normal- and wet-year scenarios are 0.81, 0.88 and 0.90, respectively, indicating that the overall coordination of reservoir-system operation improves as inflow conditions become more favorable. Among the three scenarios, the optimal scheme under the wet-year scenario has the highest coupling-coordination degree, suggesting that, under relatively abundant water-resource conditions, the reservoir system is more likely to achieve a higher degree of balance among sediment transport, electricity production and ecological water-deficit control. Accordingly, the Pareto scheme with the highest coupling-coordination degree in each representative hydrological year is selected as the recommended operation scheme for the corresponding scenario. The selected schemes are then used as the basis for subsequent analyses of coordinated operation gains and compensation allocation.

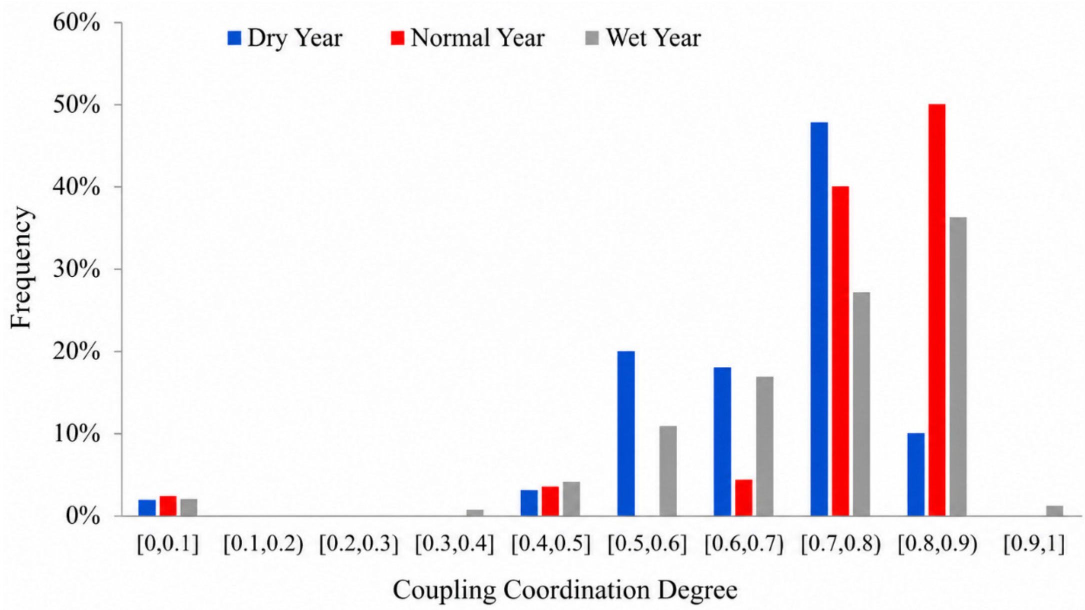

Figure 3. Distribution of coupling-coordination degree levels across Pareto non-dominated solution sets under representative hydrological conditions.

3.1.3. Gain Analysis of Coordinated Operation of the Reservoir Systems

To examine the practical plausibility of the selected results, the recommended operation scheme with the highest coupling-coordination degree in each representative hydrological year is compared with the corresponding actual operation scheme. The comparison focuses on electricity production, sediment transport load and ecological water deficit, thereby providing a practical reference for assessing whether the magnitude and direction of changes produced by the recommended schemes are consistent with the operational characteristics of the reservoir system under different hydrological conditions.

As shown in Table 6, compared with the actual operation scheme, the recommended operation scheme increases total electricity production by 1088, 1175 and 1187 GWh under the dry-, normal- and wet-year scenarios, respectively. This indicates that coordinated operation can increase electricity production under different inflow conditions. Meanwhile, the total sediment transport load decreases by 77, 87 and 71 Mt under the dry-, normal- and wet-year scenarios, respectively. This suggests that the recommended schemes selected using the maximum coupling-coordination degree criterion do not simply pursue sediment-transport benefit maximization, but instead reflect a broader trade-off among sediment transport, electricity production and ecological water-deficit control. In terms of ecological performance, the ecological water deficit of the recommended scheme under the dry-year scenario increases by 67 hm^3 compared with the actual operation scheme. This reflects the persistent trade-off between electricity production and ecological water-deficit control under relatively dry inflow conditions. Under the normal- and wet-year scenarios, the ecological water deficit decreases by 118 and 170 hm^3, respectively, with the deficit reduced to zero under the wet-year scenario. This indicates that, as inflow conditions improve, coordinated operation has a more pronounced effect on ecological water-deficit control.

From the perspective of benefit changes at the individual-reservoir level, Wanjiazhai Reservoir exhibits increased electricity production in all three representative hydrological years, accompanied by a decline in sediment transport load. This indicates that Wanjiazhai Reservoir mainly contributes to increased electricity production in the recommended operation scheme. Sanmenxia Reservoir exhibits increases in both electricity production and sediment transport load, indicating that it contributes to both electricity production and sediment transport in coordinated reservoir-system operation. Xiaolangdi Reservoir exhibits an overall increase in electricity production, whereas its sediment transport load declines. At the downstream ecological-control section, ecological water-deficit performance improves more markedly under the normal- and wet-year scenarios. Overall, coordinated operation can adjust the functional roles and benefit combinations of individual reservoirs under different hydrological conditions, shifting reservoir-system operation from a single-objective orientation toward multi-objective optimization. The differences in reservoir-specific operational gains and adjustments also provide a basis for subsequent compensation allocation.

Table 6. Comparison of objective-function values between the actual and optimized operation schemes.

Operation Scheme	Representative Hydrological Year	Electricity Production (GWh)			Sediment Transport Load (Mt)			Ecological Water Deficit (hm^3)
		Wanjiazhai	Sanmenxia	Xiaolangdi	Wanjiazhai	Sanmenxia	Xiaolangdi	Xiaolangdi
Actual operation scheme	Dry year	2957	1496	7677	63	324	267	229
	Normal year	3864	1514	12202	72	323	253	133
	Wet year	4619	1758	12574	295	457	452	170
Optimized operation scheme	Dry year	3175	1655	8388	20	376	181	296
	Normal year	4306	1684	12765	49	344	168	15
	Wet year	5006	1888	13244	212	496	425	0

The comparison with actual operation further provides a practical consistency check for interpreting the optimization results. The recommended schemes do not produce simultaneous improvements in all objectives under every hydrological condition. For example, the ecological water deficit increases under the dry-year scenario, whereas it decreases under the normal- and wet-year scenarios. This differentiated response is consistent with the trade-offs identified from the Pareto solution sets and reflects the competing demands placed on limited water resources under different inflow conditions. Together with the distributional characteristics of the Pareto solution sets and coupling-coordination degrees, this comparison provides additional evidence for assessing the practical consistency of the selected operation schemes. The comparison therefore supports the practical plausibility of the selected schemes within the examined reservoir system; however, it should not be interpreted as independent external validation of the optimization framework.

3.2. Compensation Allocation Results for Coordinated Reservoir-System Operation

3.2.1. Compensation Allocation Results Under Representative Hydrological Years

Based on the compensation-allocation indicator system and the CRITIC-TOPSIS compensation allocation model, we calculate the compensation allocation ratios of Wanjiazhai, Sanmenxia and Xiaolangdi reservoirs using the recommended operation schemes under the dry-, normal- and wet-year scenarios, represented by 2010, 2012 and 2018, respectively, as shown in Table 7.

Table 7. Compensation allocation schemes for coordinated reservoir-system operation under representative hydrological years.

Representative Hydrological Year	Wanjiazhai	Sanmenxia	Xiaolangdi
Dry year	0.16	0.05	0.79
Normal year	0.39	0.08	0.53
Wet year	0.22	0.04	0.74

Under the dry-year scenario, the compensation allocation ratios of Wanjiazhai, Sanmenxia and Xiaolangdi reservoirs are 0.16, 0.05 and 0.79, respectively. The results indicate that, under relatively dry inflow conditions, coordinated reservoir-system operation relies more strongly on the downstream key control reservoir for the integrated regulation of limited water resources. Xiaolangdi Reservoir is located at a key position for sediment regulation in the middle and lower Yellow River Basin. It assumes greater regulatory responsibility for meeting downstream ecological-discharge requirements, regulating reservoir releases and coordinating sediment-transport processes, which explains its relatively high compensation share.

Under the normal-year scenario, the compensation allocation ratios of Wanjiazhai, Sanmenxia and Xiaolangdi reservoirs are 0.39, 0.08 and 0.53, respectively. Compared with the dry-year scenario, the more moderate inflow conditions provide greater flexibility for balancing electricity production, sediment transport and ecological water-deficit control. Accordingly, the functional contributions of individual reservoirs in coordinated operation are adjusted. Wanjiazhai Reservoir plays a stronger supporting role in upstream regulation and electricity production, leading to an increased compensation ratio compared with the dry-year scenario. Xiaolangdi Reservoir continues to undertake key tasks in supporting downstream ecological discharge and sediment regulation, and its overall contribution remains high. Sanmenxia Reservoir mainly serves as an upstream–downstream linkage and provides auxiliary regulation, with a relatively smaller overall contribution under the selected indicator system.

Under the wet-year scenario, the compensation allocation ratios of Wanjiazhai, Sanmenxia and Xiaolangdi reservoirs are 0.22, 0.04 and 0.74, respectively, with the compensation share again concentrated on Xiaolangdi Reservoir. Although relatively abundant inflow under the wet-year scenario supports higher electricity production and lower ecological water deficits, it also increases the need to coordinate downstream sediment transport, flood-control safety and ecological-discharge requirements. As a key downstream regulation node, Xiaolangdi Reservoir needs to coordinate electricity production, sediment transport, flood control and the provision of ecological discharge, and therefore continues to bear substantial integrated regulatory responsibility. By contrast, Wanjiazhai Reservoir contributes to increased electricity production, but its overall compensation share remains lower than that of Xiaolangdi Reservoir. Sanmenxia Reservoir remains at a relatively low compensation level because its overall contribution under the selected engineering and operational indicators is smaller than that of the other two reservoirs.

Taken together, the compensation allocation results exhibit a consistent relative pattern across the three representative hydrological years. Although the numerical compensation shares vary with hydrological conditions, Xiaolangdi Reservoir consistently receives the largest share, followed by Wanjiazhai Reservoir, while Sanmenxia Reservoir receives the smallest share. This unchanged ranking across the dry-, normal- and wet-year scenarios indicates that the relative compensation structure is not specific to a single hydrological condition. The variation in the numerical shares further reflects changes in the relative regulatory contributions of the three reservoirs under different inflow conditions.

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3.2.2. Comparative Analysis of Different Compensation Allocation Methods

To further examine the consistency of the compensation allocation pattern, the single-indicator method and the squared-deviation method are introduced as alternative benchmark approaches. These methods differ from CRITIC-TOPSIS in their allocation basis and evaluation principles, allowing the relative compensation rankings of the three reservoirs to be compared under different methodological settings (Table 8). The comparison therefore provides evidence on whether the identified allocation pattern remains consistent when alternative compensation methods are adopted.

Table 8. Comparison of compensation allocation results for coordinated reservoir-system operation.

Allocation Method		Scenario	Wanjiazhai	Sanmenxia	Xiaolangdi
Single-indicator method	Installed capacity		0.35	0.08	0.57
	Guaranteed output	Dry year	0.28	0.18	0.54
	Long-term average electricity production	Normal year	0.31	0.11	0.58
	Effective storage capacity	Wet year	0.08	0.07	0.85
Comprehensive-indicator method	Squared-deviation method		0.30	0.10	0.60
	CRITIC-TOPSIS method	Dry year	0.16	0.05	0.79
		Normal year	0.39	0.08	0.53
		Wet year	0.22	0.04	0.74

The results of the single-indicator method show that compensation allocation ratios vary across indicators, indicating that the allocation results are sensitive to indicator selection. When installed capacity, guaranteed output and long-term average electricity production are used as allocation bases, the results mainly reflect differences among reservoirs in electricity-production capacity and stable power-supply capacity. Xiaolangdi Reservoir consistently receives a relatively high compensation share, reflecting its important role in supporting electricity production within the reservoir system. When effective storage capacity is used as the allocation basis, the compensation share of Xiaolangdi Reservoir further increases, indicating that its strong storage-regulation capacity plays a foundational role in sediment regulation, flood-control operation and ecological-discharge support. Overall, the single-indicator method has an intuitive calculation process, but its evaluation basis is relatively narrow. It therefore cannot fully capture the overall contribution, operational responsibility and benefit gain–loss relationships of reservoirs under coordinated operation.

Compared with the single-indicator method, the squared-deviation method integrates multiple indicators for allocation, thereby reducing the influence of single-indicator selection on the results to some extent and producing more balanced compensation ratios. In terms of allocation ranking, the squared-deviation method produces results that are generally consistent with those of the single-indicator method and the CRITIC-TOPSIS method, with Xiaolangdi Reservoir ranking first, Wanjiazhai Reservoir second and Sanmenxia Reservoir last. This indicates that different methods are consistent in identifying the relative functional roles of individual reservoirs in coordinated reservoir-system operation. Specifically, Xiaolangdi Reservoir acts as a key regulation node in coordinated operation, Wanjiazhai Reservoir provides a supporting function, and Sanmenxia Reservoir shows a relatively smaller overall contribution under the selected indicator system. However, the squared-deviation method mainly focuses on the integrated treatment of indicator dispersion and differentiation, and remains limited in characterizing information content, conflict relationships among indicators and the dynamic operational contributions of reservoirs.

A key feature of CRITIC-TOPSIS is that it integrates a broader range of information on reservoir engineering attributes and operational responses rather than relying on a single allocation basis. The single-indicator method reflects only one aspect of reservoir capacity at a time, while the squared-deviation method integrates several single-indicator allocation results but remains largely dependent on static engineering characteristics. In contrast, CRITIC-TOPSIS jointly incorporates static engineering attributes and dynamic operational responses, allowing compensation allocation to reflect both the long-term regulatory capacity of each reservoir and its realized contribution under specific hydrological conditions. The CRITIC procedure further determines indicator weights from both variability and inter-indicator conflict, reducing dependence on a single attribute or subjectively specified weighting structure. TOPSIS then evaluates each reservoir according to its overall proximity to the positive and negative ideal solutions across all indicators. These features allow CRITIC-TOPSIS to incorporate a broader range of information on reservoir engineering attributes and operational responses than the benchmark methods considered in this study.

Overall, the CRITIC-TOPSIS method produces the same relative reservoir ranking as the single-indicator and squared-deviation methods, with Xiaolangdi Reservoir ranked first, Wanjiazhai Reservoir second and Sanmenxia Reservoir third. This cross-method consistency provides supporting evidence that the relative compensation structure is not solely dependent on a specific allocation method. More importantly, CRITIC-TOPSIS extends the benchmark approaches by linking compensation allocation to both reservoir engineering capacity and operation-induced responses, thereby providing a more informative basis for interpreting why individual reservoirs occupy different compensation positions under coordinated operation.

4. Discussion

4.1. Hydrological Variability and Trade-Offs in Multi-Objective Reservoir Operation

Hydrological conditions fundamentally reshape the feasible space within which multiple reservoir-operation objectives can be coordinated. Under dry conditions, limited inflow must simultaneously support electricity production, ecological-discharge requirements and sediment transport, thereby intensifying competition for available water and restricting the scope for coordinated improvement. As inflow increases, water-availability constraints are progressively relaxed, providing greater operational flexibility, particularly for meeting ecological-discharge requirements. The higher coordination levels observed under normal and wet conditions can therefore be attributed to an expanded range of feasible operating combinations. Nevertheless, the persistent trade-off between electricity production and sediment transport across all hydrological scenarios indicates that greater water availability does not eliminate the underlying structural tension between these objectives. Electricity production generally benefits from maintaining reservoir storage and hydraulic head, whereas effective sediment transport depends on sufficiently large and appropriately timed reservoir releases. Improved hydrological conditions consequently broaden the feasible coordination space, but the underlying competition between storage-oriented electricity production and release-dependent sediment transport remains.

This interpretation is consistent with the broader understanding of coordinated reservoir operation in the Yellow River Basin. Previous studies have shown that multi-objective operation of cascade reservoirs can generate synergistic gains across electricity production, water supply, flood control and sediment regulation; however, the attainable combination of benefits remains sensitive to hydrological conditions [59]. Research on sediment-laden reservoir systems further indicates that water-sediment regulation requires balancing competing operational objectives rather than independently maximizing individual benefits [60,61]. Evidence from multi-objective water-sediment operation in the Yellow River Basin likewise suggests that more favorable hydrological conditions can improve both electricity-production and sediment-regulation performance while leaving important inter-objective trade-offs unresolved [62]. Building on these findings, the present analysis incorporates ecological water deficit into the multi-objective framework and further distinguishes among Pareto-efficient schemes according to their overall coordination performance. Hydrological variability therefore affects not only the attainable levels of individual operational outcomes but also the extent to which electricity production, sediment transport and ecological water-deficit control can be improved simultaneously.

4.2. Functional Differentiation and Compensation Allocation Within the Reservoir System

The compensation results reveal pronounced functional differentiation among reservoirs within the cascade system. The consistently higher compensation share assigned to Xiaolangdi Reservoir cannot be attributed solely to differences in engineering scale. Its downstream control position, large effective storage capacity, and responsibility for coordinating sediment regulation, ecological-discharge requirements, flood-control requirements and electricity production require a broader range of operational adjustments than those undertaken by the other reservoirs. Wanjiazhai Reservoir primarily contributes through upstream regulation and support for electricity production, whereas Sanmenxia Reservoir performs an intermediate role in regulating reservoir releases and sediment-transport processes between the upstream and downstream reaches. The resulting compensation pattern therefore reflects differences in regulatory responsibilities and operational contributions along the cascade rather than a simple proportional allocation based on installed capacity, storage capacity or long-term average electricity production. Such functional differentiation is inherent in coordinated reservoir operation because reservoirs at different positions within a cascade are subject to distinct hydraulic conditions, operating constraints, and downstream management requirements [63].

This interpretation further highlights the distinction between regulatory capacity and realized operational contribution. Static engineering attributes characterize the potential capacity of a reservoir to support coordinated operation, whereas changes in electricity production, reservoir water level and reservoir release reflect the actual adjustments undertaken under specific operating conditions. Compensation mechanisms based exclusively on fixed engineering characteristics may therefore fail to capture the redistribution of operational burdens arising from coordinated regulation [64]. Integrating static attributes with dynamic operational responses establishes a closer connection between compensation allocation and the operational processes through which system-wide benefits are achieved [65]. The stability of the reservoir ranking across representative hydrological conditions and alternative allocation methods suggests that the relative compensation pattern is comparatively consistent, whereas variations in the absolute allocation shares indicate that the magnitude of compensation remains sensitive to hydrological conditions and operational responses. Compensation allocation should therefore distinguish between relatively stable functional differences among reservoirs and scenario-dependent variations in their realized operational contributions.

4.3. Comparison with Broader Regulated-River Management and Implications for Compensation Design

The trade-offs identified in the Yellow River reservoir system are consistent with a broader challenge faced by large regulated rivers, where reservoir operation must reconcile electricity production, water supply, flood control, sediment management, and ecological requirements under limited and highly variable water availability. Evidence from large regulated river systems indicates that greater operational flexibility can improve the balance among competing objectives but cannot fully eliminate conflicts between storage-oriented economic uses and release-dependent environmental functions [66,67]. Electricity production generally benefits from maintaining reservoir storage and regulating releases in response to power demand, whereas ecological restoration and sediment management often require adjustments in release magnitude, timing, and variability. Similar trade-offs have been observed in heavily regulated river systems, where environmental-flow restoration can generate measurable ecological gains while imposing corresponding costs on electricity production [68]. The Yellow River case adds an additional dimension to this broader pattern because sediment transport constitutes a core operational objective rather than merely a secondary environmental constraint. Coordinated operation must therefore balance economic performance, ecological-discharge requirements, and sediment-transport processes that directly affect reservoir storage, downstream channel stability, and the long-term functioning of the regulated river system.

These broader comparisons reinforce the need to link coordinated reservoir operation with an adaptive compensation mechanism. In multi-reservoir systems, system-wide benefits arise from adjustments in the operating decisions of individual reservoirs, while the distribution of these benefits may not correspond to the distribution of regulatory burdens. Studies of cooperative reservoir operation have consequently emphasized that the practical sustainability of joint operation depends on the ability to identify and redistribute incremental system benefits among participating reservoirs according to their contributions. For the Yellow River reservoir system, this implies that compensation should not be treated as a fixed redistribution rule independent of the operating process. The relatively stable compensation ranking identified in this study can provide a basis for identifying compensation priorities, whereas the scenario-dependent allocation shares can be adjusted according to hydrological conditions and realized operational contributions. Such an arrangement can improve the fairness and adaptability of benefit redistribution, reduce persistent mismatches between regulatory responsibilities and allocated benefits, and thereby support the long-term institutional and economic sustainability of coordinated reservoir-system management.

4.4. Practical Implications for Sustainable and Adaptive Reservoir Management

The results support a hydrologically differentiated decision framework rather than a uniform operating rule applied across all inflow conditions. Under dry conditions, intensified competition among electricity production, sediment transport, and ecological water-deficit control narrows the feasible range of coordinated solutions and increases the importance of explicitly defining ecological-discharge requirements and acceptable trade-off boundaries before selecting an operating scheme. Under normal and wet conditions, greater water availability expands the feasible coordination space and provides additional flexibility for balancing electricity production with sediment-transport requirements. The Pareto-efficient solution sets obtained under different hydrological scenarios can therefore be interpreted as scenario-specific decision spaces, whereas the coupling-coordination degree provides an additional criterion for identifying schemes with more balanced performance across multiple objectives. This framework allows reservoir managers to adapt operating strategies to prevailing hydrological and sediment conditions while reducing the risk that gains in one objective are achieved at the persistent expense of other economic or environmental functions.

The compensation mechanism should be designed with a similarly adaptive structure. Static engineering attributes can provide a relatively stable basis for characterizing long-term regulatory capacity, whereas realized operational contributions should be updated according to observed reservoir responses during each operating period. Changes in electricity production, reservoir water level, reservoir release, ecological-discharge support, and sediment-transport performance can be incorporated into periodic compensation assessments to reflect actual regulatory responsibilities. The cross-scenario and cross-method comparisons indicate that the relative compensation ranking is more stable than the exact allocation shares, suggesting that the model is more appropriate for identifying relative compensation priorities and reference ranges than for determining fixed long-term payment coefficients. A practical institutional arrangement can therefore combine a stable baseline component reflecting engineering capacity with a dynamic component linked to realized operational contributions. Such a structure can improve the adaptability, fairness, and continuity of coordinated reservoir management and provide institutional support for balancing economic performance, ecological requirements, and long-term system functionality under changing hydrological conditions.

5. Conclusions and Implications

5.1. Conclusions

In this study, we address coordinated reservoir-system operation and compensation allocation, focusing on the Wanjiazhai, Sanmenxia and Xiaolangdi reservoirs in the middle and lower Yellow River Basin. The years 2010, 2012 and 2018 are selected to represent dry-, normal- and wet-year scenarios, respectively. A multi-objective optimal operation model is constructed, and the NSGA-II algorithm is used to derive coordinated operation schemes for the three representative hydrological years. On this basis, a compensation-allocation indicator system is developed by incorporating both static engineering attributes and dynamic operational contributions of reservoirs. The CRITIC-TOPSIS model is applied to calculate the compensation shares of individual reservoirs in coordinated operation, with the single-indicator method and the squared-deviation method used as benchmarks to examine the reasonableness of the allocation results. The results show that the coordinated operation schemes exhibit relatively high coupling-coordination levels across representative hydrological years, with maximum coupling-coordination degrees of 0.81, 0.88 and 0.90 under the dry-, normal- and wet-year scenarios, respectively. Compared with the actual operation scheme, the recommended operation scheme increases total electricity production under all three representative hydrological conditions and achieves more balanced outcomes in sediment transport and ecological water-deficit control. The compensation allocation results show that, under different inflow conditions, Xiaolangdi Reservoir consistently receives the largest compensation share, followed by Wanjiazhai Reservoir, while Sanmenxia Reservoir receives the smallest share. The CRITIC-TOPSIS results yield the same relative reservoir ranking as the benchmark allocation methods, while incorporating both static engineering characteristics and dynamic operational responses into the allocation process. This cross-method consistency provides supporting evidence for the plausibility of the identified contribution pattern, while the multidimensional indicator structure provides an additional basis for interpreting functional differences among reservoirs.

The proposed framework links multi-objective operation, coordination-oriented scheme selection, and compensation allocation within a unified analytical process. It provides a quantitative approach for identifying trade-offs among sediment transport, electricity production, and ecological water-deficit control while connecting system-level operation outcomes with the differentiated contributions of individual reservoirs. From the perspective of sustainable reservoir-system management, the framework contributes by jointly addressing environmental requirements, economic performance, and the institutional distribution of regulatory responsibilities and benefits among participating reservoirs. The integration of adaptive operation with contribution-based compensation provides a basis for improving the long-term environmental, economic, and institutional sustainability of coordinated reservoir management in the Yellow River Basin. Several limitations should nevertheless be acknowledged. The present analysis is based on three representative hydrological years and one reservoir system in the middle and lower Yellow River Basin, which may constrain the generalizability of the findings to a broader range of hydrological conditions and reservoir configurations. In addition, the hydrological and sediment records, reservoir operation data, and prescribed ecological-discharge requirements used as model inputs are subject to varying degrees of observational, aggregation, and parameter uncertainty. Because these uncertainties are not explicitly propagated through the optimization and allocation procedures, they may affect the estimated objective values and the exact numerical compensation shares; however, the comparative patterns identified across representative hydrological conditions remain informative for interpreting relative operational trade-offs and reservoir-specific contributions. The stability of the optimization results is assessed mainly through the distributional characteristics of the Pareto solution sets, the coupling-coordination degree distributions, and comparison with actual operation rather than through confidence intervals derived from repeated independent optimization runs. Similarly, the consistency of the compensation allocation results is evaluated primarily from the stability of reservoir rankings across different hydrological scenarios and alternative allocation methods. A systematic sensitivity analysis of the CRITIC-derived indicator weights has also not yet been conducted, and the exact compensation shares may therefore remain sensitive to changes in the weighting structure. Future research could incorporate uncertainty propagation for hydrological, sediment, and ecological-discharge inputs; repeated independent optimization runs; alternative indicator-weight settings; longer hydrological sequences; extreme hydrological conditions; and larger reservoir systems to more comprehensively evaluate the stability, robustness, transferability, and sustainability implications of the proposed framework.

5.2. Policy Implications

(1) Establish an institutionalized joint-operation mechanism for basin-wide reservoir coordination

The multiple functions performed by reservoir systems in the Yellow River Basin require coordinated decision-making beyond the optimization of individual reservoir operation. A basin-wide joint-operation mechanism should therefore be established to clarify the respective responsibilities of reservoir operators, basin-management agencies, power-sector authorities, and ecological-management departments in coordinated scheduling. The mechanism should establish procedures for annual operation planning, inter-reservoir consultation, ecological-discharge assurance, sediment-regulation coordination, and emergency response, thereby translating model-based coordination into an institutionalized management process. In particular, the functional differentiation among Wanjiazhai, Sanmenxia, and Xiaolangdi reservoirs should be reflected in the allocation of regulatory responsibilities, enabling upstream storage support, intermediate reservoir-release and sediment regulation, and downstream integrated control to be coordinated within a unified operational framework.

(2) Establish standardized compensation rules and responsibility-recognition procedures

The implementation of inter-reservoir compensation requires a transparent institutional framework for identifying regulatory responsibilities and determining compensation eligibility. Standardized procedures should be established to verify the regulatory tasks undertaken by individual reservoirs, including deviations from conventional operating patterns, additional ecological-discharge obligations, sediment-regulation responsibilities, and associated opportunity costs. Compensation decisions should be supported by documented operating records and jointly verified by the relevant management agencies to reduce uncertainty in contribution recognition and benefit attribution. On this

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basis, compensation standards, calculation procedures, funding responsibilities, settlement arrangements, and review requirements should be incorporated into formal reservoir-coordination rules, thereby transforming compensation from an ex post analytical outcome into an enforceable component of coordinated reservoir management.

(3) Establish a periodic evaluation and trigger-based adjustment mechanism

The effectiveness of coordinated reservoir operation and compensation arrangements should be evaluated regularly rather than relying on fixed rules established at a single point in time. Annual or seasonal assessments should be conducted to evaluate whether coordinated operation has achieved the expected outcomes in electricity production, sediment regulation, ecological-discharge support, and inter-reservoir benefit distribution. In addition to routine evaluations, reassessment procedures should be triggered by extreme droughts, major flood events, abrupt changes in sediment conditions, or substantial deviations from expected ecological requirements. The evaluation results can then provide a basis for adjusting operational priorities, compensation standards, and responsibility arrangements, thereby maintaining the adaptability of the coordination mechanism under changing hydrological and management conditions.

(4) Strengthen basin-wide data integration and decision-support infrastructure

Effective coordinated reservoir operation and compensation management require consistent, traceable, and comparable data across reservoirs and management agencies. Basin-wide data standards should therefore be established for inflow, reservoir water level, reservoir release, sediment concentration, electricity production, ecological-discharge conditions, and operating records, ensuring that regulatory contributions and compensation claims are assessed on a consistent information basis. Data-sharing protocols should further specify reporting frequency, verification responsibilities, access authority, and archival requirements for reservoir operators and basin-management agencies. On this basis, standardized data can be integrated into a unified decision-support platform to support operation-scheme evaluation, contribution assessment, compensation verification, and post-operation review, thereby improving the transparency, consistency, and accountability of coordinated reservoir management.

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References

1. Wang, S.; Song, S.; Zhang, H.; Yu, L.; Jiao, C.; Li, C.; Wu, X.; Zhao, W.; Best, J.; Roberts, P.; et al. Anthropogenic impacts on the Yellow River Basin. *Nat. Rev. Earth Environ.* **2025**, *6*, 656–671. [CrossRef]
2. Zhang, Q.; Zhang, Z.; Shi, P.; Singh, V.P.; Gu, X. Evaluation of ecological instream flow considering hydrological alterations in the Yellow River basin, China. *Glob. Planet. Change* **2018**, *160*, 61–74. [CrossRef]
3. Wei, J.; Lei, Y.; Liu, L.; Yao, H. Water scarcity risk through trade of the Yellow River Basin in China. *Ecol. Indic.* **2023**, *154*, 110893. [CrossRef]
4. Wu, X.; Bi, N.; Syvitski, J.; Saito, Y.; Xu, J.; Nittrouer, J.A.; Bianchi, T.S.; Yang, Z.; Wang, H. Can reservoir regulation along the Yellow River be a sustainable way to save a sinking delta? *Earths Future* **2020**, *8*, e2020EF001587. [CrossRef]
5. Bai, T.; Wu, L.; Chang, J.-X.; Huang, Q. Multi-objective optimal operation model of cascade reservoirs and its application on water and sediment regulation. *Water Resour. Manag.* **2015**, *29*, 2751–2770. [CrossRef]
6. Bai, T.; Chang, J.-X.; Chang, F.-J.; Huang, Q.; Wang, Y.-M.; Chen, G.-S. Synergistic gains from the multi-objective optimal operation of cascade reservoirs in the Upper Yellow River basin. *J. Hydrol.* **2015**, *523*, 758–767. [CrossRef]
7. Jin, W.; Chang, J.; Wang, Y.; Bai, T. Long-term water-sediment multi-objectives regulation of cascade reservoirs: A case study in the Upper Yellow River, China. *J. Hydrol.* **2019**, *577*, 123978. [CrossRef]
8. Chen, L.; Ge, L.; Wang, D.; Zhong, W.; Zhan, T.; Deng, A. Multi-objective water-sediment optimal operation of cascade reservoirs in the Yellow River Basin. *J. Hydrol.* **2022**, *609*, 127744. [CrossRef]
9. Ma, Y.; Zhong, P.-A.; Xu, B.; Bing, J.; Zhang, Y. Multiobjective and joint operation model for multistakeholder cascade hydropower system. *J. Water Resour. Plan. Manag.* **2020**, *146*, 04020083. [CrossRef]
10. Haken, H. Synergetics of brain function. *Int. J. Psychophysiol.* **2006**, *60*, 110–124. [CrossRef]
11. Castelletti, A.; Pianosi, F.; Restelli, M. A multiobjective reinforcement learning approach to water resources systems operation: Pareto frontier approximation in a single run. *Water Resour. Res.* **2013**, *49*, 3476–3486. [CrossRef]
12. Giuliani, M.; Castelletti, A.; Pianosi, F.; Mason, E.; Reed, P.M. Curses, tradeoffs, and scalable management: Advancing evolutionary multiobjective direct policy search to improve water reservoir operations. *J. Water Resour. Plan. Manag.* **2016**, *142*, 04015050. [CrossRef]
13. Harou, J.J.; Pulido-Velazquez, M.; Rosenberg, D.E.; Medellín-Azuara, J.; Lund, J.R.; Howitt, R.E. Hydro-economic models: Concepts, design, applications, and future prospects. *J. Hydrol.* **2009**, *375*, 627–643. [CrossRef]
14. Jager, H.I.; Smith, B.T. Sustainable reservoir operation: Can we generate hydropower and preserve ecosystem values? *River Res. Appl.* **2008**, *24*, 340–352. [CrossRef]
15. Poff, N.L.R.; Olden, J.D.; Merritt, D.M.; Pepin, D.M. Homogenization of regional river dynamics by dams and global biodiversity implications. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 5732–5737. [CrossRef]
16. Tilmant, A.; Kinzelbach, W. The cost of noncooperation in international river basins. *Water Resour. Res.* **2012**, *48*, W01503. [CrossRef]
17. Arjoon, D.; Tilmant, A.; Herrmann, M. Sharing water and benefits in transboundary river basins. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 2135–2150. [CrossRef]
18. Yeh, W.W.G. Reservoir management and operations models: A state-of-the-art review. *Water Resour. Res.* **1985**, *21*, 1797–1818. [CrossRef]
19. Labadie, J.W. Optimal operation of multireservoir systems: State-of-the-art review. *J. Water Resour. Plan. Manag.* **2004**, *130*, 93–111. [CrossRef]
20. Rani, D.; Moreira, M.M. Simulation-optimization modeling: A survey and potential application in reservoir systems operation. *Water Resour. Manag.* **2010**, *24*, 1107–1138. [CrossRef]
21. Reddy, M.J.; Kumar, D.N. Multi-objective particle swarm optimization for generating optimal trade-offs in reservoir operation. *Hydrol. Process.* **2007**, *21*, 2897–2909. [CrossRef]
22. Reddy, M.J.; Kumar, D.N. Multiobjective differential evolution with application to reservoir system optimization. *J. Comput. Civ. Eng.* **2007**, *21*, 136–146. [CrossRef]
23. Chang, L.C.; Chang, F.-J. Multi-objective evolutionary algorithm for operating parallel reservoir system. *J. Hydrol.* **2009**, *377*, 12–20. [CrossRef]
24. Wang, L.; Li, Y.; Wang, Y.; Guo, J.; Xia, Q.; Tu, Y.; Nie, P. Compensation benefits allocation and stability evaluation of cascade hydropower stations based on Variation Coefficient-Shapley Value Method. *J. Hydrol.* **2021**, *599*, 126277. [CrossRef]

25. Suzuki, M.; Nakayama, M. The cost assignment of the cooperative water resource development: A game theoretical approach. *Manag. Sci.* **1976**, *22*, 1081–1086. [CrossRef]
26. Yuan, L.; Liu, H.; Lu, Y.; Zhou, C.; Zhou, C.; Lu, Y. Multi-objective integrated decision method of cascade hydropower stations based on optimization algorithm and evaluation model. *J. Hydrol.* **2024**, *638*, 131533. [CrossRef]
27. Omer, A.; Elagib, N.A.; Zhuguo, M.; Saleem, F.; Mohammed, A. Water scarcity in the Yellow River Basin under future climate change and human activities. *Sci. Total Environ.* **2020**, *749*, 141446. [CrossRef]
28. Jin, W.; Wang, Y.; Chang, J.; Wang, X.; Niu, C.; Wang, Y.; Peng, S. Multi-objective synergetic reservoir operation in a sediment-laden river. *J. Hydrol.* **2021**, *599*, 126295. [CrossRef]
29. Liu, G.; Jiang, E.; Li, D.; Li, J.; Wang, Y.; Zhao, W.; Yang, Z. Annual multi-objective optimization model and strategy for scheduling cascade reservoirs on the Yellow River mainstream. *J. Hydrol.* **2025**, *659*, 133306. [CrossRef]
30. Kong, D.; Miao, C.; Wu, J.; Duan, Q.; Sun, Q.; Ye, A.; Di, Z.; Gong, W. The hydro-environmental response on the lower Yellow River to the water–sediment regulation scheme. *Ecol. Eng.* **2015**, *79*, 69–79. [CrossRef]
31. Wang, Y.; Liu, P.; Dou, M.; Li, H.; Ming, B.; Gong, Y.; Yang, Z. Reservoir ecological operation considering outflow variations across different time scales. *Ecol. Indic.* **2021**, *125*, 107582. [CrossRef]
32. Wang, H.; Wu, X.; Bi, N.; Li, S.; Yuan, P.; Wang, A.; Syvitski, J.P.; Saito, Y.; Yang, Z.; Liu, S.; et al. Impacts of the dam-orientated water-sediment regulation scheme on the lower reaches and delta of the Yellow River (Huanghe): A review. *Glob. Planet. Change* **2017**, *157*, 93–113. [CrossRef]
33. Zhang, J.; Shang, Y.; Liu, J.; Lu, J.; Wei, S.; Wan, Z.; Luo, Q.; Chen, C.; Tong, L.; Wang, Q.; et al. Optimisation of reservoir operation mode to improve sediment transport capacity of silt-laden rivers. *J. Hydrol.* **2021**, *594*, 125951. [CrossRef]
34. Cheng, Y.; Xia, J.; Zhou, M.; Deng, S.; Li, Z. Adjustment of flood discharge capacity with varying boundary conditions in a braided reach of the Lower Yellow River. *J. Geogr. Sci.* **2021**, *31*, 1615–1632. [CrossRef]
35. Kondolf, G.M.; Gao, Y.; Annandale, G.W.; Morris, G.L.; Jiang, E.; Zhang, J.; Cao, Y.; Carling, P.; Fu, K.; Guo, Q.; et al. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earths Future* **2014**, *2*, 256–280. [CrossRef]
36. Wu, X.; Feng, X.; Fu, B.; Yin, S.; He, C. Managing erosion and deposition to stabilize a silt-laden river. *Sci. Total. Environ.* **2023**, *881*, 163444. [CrossRef]
37. Jiang, Z.; Liu, P.; Ji, C.; Zhang, H.; Chen, Y. Ecological flow considered multi-objective storage energy operation chart optimization of large-scale mixed reservoirs. *J. Hydrol.* **2019**, *577*, 123949. [CrossRef]
38. Feng, Z.; Niu, W.; Cheng, C. Optimization of hydropower reservoirs operation balancing generation benefit and ecological requirement with parallel multi-objective genetic algorithm. *Energy* **2018**, *153*, 706–718. [CrossRef]
39. Zhou, J.; Tang, Q.; Yang, K.; Jiang, R.; Pan, W.; Ren, Y.; Qin, J.; Chen, D.; Lu, H. Improved hydropower simulation for China based on a newly developed hydropower database. *J. Hydrol.* **2025**, *657*, 133022. [CrossRef]
40. Xie, Y.; Guo, S.; Zhong, S.; He, Z.; Liu, P.; Zhou, Y. Optimal allocation of flood prevention storage and dynamic operation of water levels to increase cascade reservoir hydropower generation. *Renew. Energy* **2024**, *228*, 120676. [CrossRef]
41. Zhang, Y.; Wang, X.; Feng, T.; Lian, J.; Luo, P.; Rijal, M.; Wei, W. Real-time predictive control assessment of low-water head hydropower station considering power generation and flood discharge. *J. Hydrol.* **2024**, *645*, 132204. [CrossRef]
42. Suen, J.; Eheart, J.W. Reservoir management to balance ecosystem and human needs: Incorporating the paradigm of the ecological flow regime. *Water Resour. Res.* **2006**, *42*, W03417. [CrossRef]
43. Suen, J.-P. Determining the ecological flow regime for existing reservoir operation. *Water Resour. Manag.* **2011**, *25*, 817–835. [CrossRef]
44. Ai, Y.; Ma, Z.; Xie, X.; Huang, T.; Cheng, H. Optimization of ecological reservoir operation rules for a northern river in China: Balancing ecological and socio-economic water use. *Ecol. Indic.* **2022**, *138*, 108822. [CrossRef]
45. Zhu, S.; Dong, Z.; Wu, S.; Fu, G.; Li, Z.; Meng, J.; Shao, Y.; Zhang, K. Evaluation of reservoir-induced ecological flow with consideration of ecological responses to multiple hydrological alterations: A case study in the Feiyun River Basin, China. *Ecol. Indic.* **2023**, *154*, 110859. [CrossRef]
46. Gao, Y.; Vogel, R.M.; Kroll, C.N.; Poff, N.L.; Olden, J.D. Development of representative indicators of hydrologic alteration. *J. Hydrol.* **2009**, *374*, 136–147. [CrossRef]
47. Li, X.; Guo, S.; Liu, P.; Chen, G. Dynamic control of flood limited water level for reservoir operation by considering inflow uncertainty. *J. Hydrol.* **2010**, *391*, 124–132. [CrossRef]
48. Wu, C.; Wang, Z.; Yue, P.; Lai, Z.; Wang, Y. Research on optimal operation of cascade reservoirs under complex water-level flow output constraints. *Water* **2024**, *16*, 2963. [CrossRef]
49. Wang, Z.; Dai, R.; Wang, W.; Jie, J.; Ye, Q. Many-objective optimization scheduling of cascade reservoirs in small watersheds based on an evolutionary multitasking framework. *Sci. Rep.* **2025**, *15*, 20523. [CrossRef]
50. Srinivas, N.; Deb, K. Muiltiobjective optimization using nondominated sorting in genetic algorithms. *Evol. Comput.* **1994**, *2*, 221–248. [CrossRef]

51. Reed, P.M.; Hadka, D.; Herman, J.; Kasprzyk, J.; Kollat, J. Evolutionary multiobjective optimization in water resources: The past, present, and future. *Adv. Water Resour.* **2013**, *51*, 438–456. [CrossRef]
52. Reddy, M.J.; Kumar, D.N. Optimal reservoir operation using multi-objective evolutionary algorithm. *Water Resour. Manag.* **2006**, *20*, 861–878. [CrossRef]
53. Deb, K.; Pratap, A.; Agarwal, S.; Meyarivan, T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **2002**, *6*, 182–197. [CrossRef]
54. Sui, G.; Wang, H.; Cai, S.; Cui, W. Coupling coordination analysis of resources, economy, and ecology in the Yellow River Basin. *Ecol. Indic.* **2023**, *156*, 111133. [CrossRef]
55. Cui, Y.; Zhou, Y.; Jin, J.; Zhang, L.; Wu, C.; Ning, S. Coordinated development evaluation and diagnosis of regional water resources-social economy-ecological environment system based on mechanical model and risk matrix. *J. Hydrol.* **2024**, *633*, 131013. [CrossRef]
56. Gebre, S.L.; Cattrysse, D.; Van Orshoven, J. Multi-criteria decision-making methods to address water allocation problems: A systematic review. *Water* **2021**, *13*, 125. [CrossRef]
57. Li, D.; Zhao, J.; Govindaraju, R.S. Water benefits sharing under transboundary cooperation in the Lancang-Mekong River Basin. *J. Hydrol.* **2019**, *577*, 123989. [CrossRef]
58. Dong, Z.; Wang, J. Quantitative standard of eco-compensation for the water source area in the middle route of the South-to-North Water Transfer Project in China. *Front. Environ. Sci. Eng. China* **2011**, *5*, 459–473. [CrossRef]
59. Wang, Y.; Tang, F.; Jiang, E.; Wang, X.; Zhao, J. Optimizing hydropower generation and sediment transport in Yellow River basin via cooperative game theory. *J. Hydrol.* **2022**, *614*, 128581. [CrossRef]
60. Bai, T.; Wei, J.; Chang, F.-J.; Yang, W.; Huang, Q. Optimize multi-objective transformation rules of water-sediment regulation for cascade reservoirs in the Upper Yellow River of China. *J. Hydrol.* **2019**, *577*, 123987. [CrossRef]
61. Jin, W.; Niu, Z.; Bai, T.; Song, C. Multi-objective synergistic equilibrium regulation for cascade reservoirs system. *J. Hydrol.* **2025**, *664*, 134454. [CrossRef]
62. Feng, Z.K.; Shen, L.; Guan, T.S.; Long, A.H.; Xu, Q.; Chen, X.; Niu, W.J. Multi-objective optimization of water–sediment-ecology coordinated operation for cascade reservoirs in the Yellow River Basin. *J. Hydrol.* **2026**, *678*, 136069. [CrossRef]
63. Lu, S.; Shang, Y.; Li, W.; Peng, Y.; Wu, X. Economic benefit analysis of joint operation of cascaded reservoirs. *J. Clean. Prod.* **2018**, *179*, 731–737. [CrossRef]
64. Chen, Y.; Li, J.; Lu, H.; Xia, J. The dynamic benefit compensation in a multi-reservoir system based on importance analysis. *J. Clean. Prod.* **2020**, *249*, 119402. [CrossRef]
65. Shen, J.; Cheng, C.; Zhang, X.; Zhou, B. Coordinated operations of multiple-reservoir cascaded hydropower plants with cooperation benefit allocation. *Energy* **2018**, *153*, 509–518. [CrossRef]
66. Tilmant, A.; Beevers, L.; Muyunda, B. Restoring a flow regime through the coordinated operation of a multireservoir system: The case of the Zambezi River basin. *Water Resour. Res.* **2010**, *46*, W07533. [CrossRef]
67. Adams, L.E.; Lund, J.R.; Moyle, P.B.; Quiñones, R.M.; Herman, J.D.; O'REar, T.A. Environmental hedging: A theory and method for reconciling reservoir operations for downstream ecology and water supply. *Water Resour. Res.* **2017**, *53*, 7816–7831. [CrossRef]
68. Widén, Å.; Renöfält, B.M.; Degerman, E.; Wisaeus, D.; Jansson, R. Environmental flow scenarios for a regulated river system: Projecting catchment-wide ecosystem benefits and consequences for hydroelectric production. *Water Resour. Res.* **2022**, *58*, e2021WR030297. [CrossRef]