A Cooperative Game-Theoretic Framework for Multi-Objective Reservoir Operation Decision-Making

Junbo Liu [1], Changwen Li [2,3,4]*, Han Zhang [4], Liangzhe He [4], Chenggang Li [1], Changlong Gao [1], Guanghui Wu [2,3,4], Chenxi Du [2,3,4]

[1] Electric Power Research Institute of State Grid Jilin Electric Power Co., Ltd, Changchun 130021, China
[2] Hubei Key Laboratory of Construction and Management in Hydropower Engineering, China Three Gorges University, Yichang 443002, China
dlaminilungelo680@gmail.com, lichangwen@alumni.hust.edu.cn
[3] Three Gorges Digital Intelligence Institute, China Three Gorges University, Yichang 443002, China
[4] College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang 443002, China

*lichangwen@alumni.hust.edu.cn

Abstract. The operational scheduling of cascaded reservoirs presents a significant challenge due to the complex landscape of conflicting objectives and stakeholder interests. Existing multi-objective decision-making methods often conflate these two distinct conflicts into a single, monolithic evaluation, which can obscure whether a solution is sub-optimal due to imbalanced objectives or unstable stakeholder coalitions. To address this gap, this paper proposes a two-stage cooperative game-theoretic framework. This framework decouples the complex decision problem into two distinct, sequential games: the explicit decoupling of inter-objective conflicts (modeled as the "Target Game") and inter-stakeholder conflicts (modeled as the "Stakeholder Game"). This decoupling enables independent assessment of two critical dimensions that were previously intertwined, overcoming the limitations of monolithic evaluation approaches. In the first stage, a “Target Game” is formulated to assess the balance of benefit distribution among operational objectives, quantified by the variance of the Shapley value. In the second stage, a “Stakeholder Game” is established to evaluate the stability of cooperation among stakeholder coalitions, measured by the degree of Core constraint violation. A final decision is then made by synthesizing these two dimensions using the weighted ideal point method. The framework's effectiveness is demonstrated through a case study on a representative two-reservoir system. The results indicate that the proposed approach can identify a solution that, while involving a calculated trade-off in power generation, yields substantial improvements in both ecological conditions and flood safety. This study contributes a structured and analytically robust methodology for selecting holistically superior strategies in complex reservoir systems.

Keywords: Reservoir Systems, Multi-objective Decision-Making, Cooperative Game Theory, Shapley Value, The Core.

S. Sing et al. (eds.), *Proceedings of the 2025 7th International Conference on Civil Architecture and Urban Engineering (ICCAUE 2025)*, Atlantis Highlights in Engineering 43,
https://doi.org/10.2991/978-94-6239-682-1_17

1 Introduction

The coordinated operation of reservoirs in series is pivotal for the integrated management and utilization of water resources, yet their scheduling is a notoriously complex task[1]. In systems composed of two such reservoirs, this complexity is particularly acute, arising from two distinct, yet intertwined, sources of conflict: (1) inter-objective conflict, where optimizing one objective often compromises another, and (2) inter-stakeholder conflict, involving the competing interests of different entities, such as upstream and downstream beneficiaries.

To address these challenges, Multi-Objective Evolutionary Algorithms, such as NSGA-III, have been widely employed to generate a set of non-dominated solutions known as the Pareto front. This provides decision-makers with a landscape of optimal trade-offs. However, the "last-mile" problem of selecting a single, final solution from this vast set remains a significant challenge. While various Multi-Criteria Decision-Making methods have been applied[2,3], they often fail to capture the strategic interactions inherent in the system[4].

Cooperative game theory offers a more sophisticated lens for this decision problem by viewing the system as a grand coalition seeking to maximize joint benefits[5]. However, existing game-theoretic applications in reservoir operation tend to conflate the two aforementioned types of conflict, for instance, by mixing objectives and stakeholders as players in a single, oversimplified game. This can obscure the true nature of the trade-offs and lead to solutions that are either unbalanced across objectives or unstable among stakeholders[6]. For instance, a solution that heavily favors power generation might appear acceptable in a monolithic game, yet our decoupled approach would reveal its sub-optimality by identifying both a severe lack of inter-objective balance (due to neglecting ecology) and a high risk of inter-stakeholder instability (as downstream users would likely reject it).To address this critical gap, this paper proposes a two-stage cooperative game-theoretic framework that decouples these two conflicts. The primary contribution of this study is the development of a systematic framework that models the decision process as two sequential cooperative games. The first, a "Target Game," is formulated to exclusively assess the inter-objective balance of each solution using Shapley value variance as a metric. The second, a "Stakeholder Game, " is designed to evaluate the inter-stakeholder stability using the Core as a solution concept. The effectiveness of this dual-game framework is then demonstrated through a representative case study of a two-reservoir system, showcasing its ability to identify a holistically superior operational strategy.

2 Methodology

The decision-making framework proposed in this study integrates multi-objective optimization with a two-stage cooperative game-theoretic evaluation. It consists of three main steps: (1) Pareto front generation and screening; (2) a two-stage game-theoretic evaluation for balance and stability[7]; and (3) final solution synthesis.

2.1 Pareto Solutions Generation and Screening

First, a multi-objective optimization model for cascade reservoir operation is established, which aims to simultaneously maximize hydropower generation, minimize flood control risk, and minimize ecological flow deviation. This model is solved using the NSGA-III algorithm[8-10] to obtain a large set of Pareto-optimal solutions, forming the initial Pareto front. To reduce decision complexity, a hybrid screening method is then applied to extract a smaller, representative subset of candidate solutions. The effectiveness of this screening is quantitatively assessed using the diversity metric (Δ), which measures the uniformity and spread of the solutions.

2.2 Two-Stage Cooperative Game-Theoretic Evaluation

This section details the core of the proposed framework, wherein the evaluation process is decoupled into two sequential games. For each candidate solution, the following analysis is performed:

Stage 1: The "Target Game" for Inter-Objective Balance. To evaluate the fairness of benefit distribution among the different operational objectives, the first cooperative game, termed the "Target Game," is formulated. In this game, the players are the M operational objectives themselves: N = {Generation, Ecology, Flood Control}. For a given solution, the values of its objectives are first normalized to a [0,1] scale to eliminate dimensional differences and ensure comparability. The characteristic function v(S) for any coalition of objectives S ⊆ N is then defined as the sum of the normalized values of the objectives within it. The evaluation metric for balance is the variance of the Shapley values calculated for each objective. A smaller variance indicates a more balanced distribution of benefits.

$$\sigma_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n-|S|-1)!}{n!} [v(S \cup \{i\}) - v(S)] \tag{1}$$

where, σ_i is the Shapley value of objective i; N is the set of all objectives; S is any subset of N that does not contain i; $|S|$ is the cardinality of subset S; n is the total number of objectives; and $v(S)$ is the characteristic function of the coalition S.

$$B = \frac{1}{n} \sum_{i=1}^{n} (\sigma_i - \overline{\sigma})^2 \tag{2}$$

where, B is the variance of the Shapley values; σ_i is the Shapley value of objective i; and σ_i is the average of the Shapley values for all objectives.

Stage 2: The "Stakeholder Game" for Inter-Stakeholder Stability. To evaluate the stability of cooperation among key stakeholders, the "Stakeholder Game" is formulated. The players in this game are K stakeholder coalitions, formed by aggregating objectives based on shared interests. In this study, three primary stakeholders are defined: the Upstream Alliance, the Downstream Alliance, and the Flood Control Alliance. The characteristic function v(S) for a stakeholder coalition S'⊆ N' is defined as the sum of the normalized values of the objectives associated with it. The evaluation metric for stability is the degree of Core constraint violation (δ). A smaller δ indicates the solution is more stable. This total violation is calculated by summing the violations of efficiency, individual rationality, and group rationality constraints, which are checked against a fair payoff allocation scheme derived from the Shapley values of this stakeholder game.

$$\delta(x) = |\sum_{i \in N'} x_i - v'(N')| + \sum_{i \in N'} max\{0, v'(i) - x_i\} + \sum_{S \subset N', |S| \geq 2} max\{0, v'(S) - \sum_{i \in S} x_i\} \quad (3)$$

where, $\delta(x)$ is the degree of Core constraint violation for a given allocation x; N' is the set of all players; S is any sub-coalition of N'; x_i is the payoff allocated to player i; and $v'(S)$ is the value of the characteristic function for coalition S.Decision Synthesis with Weighted Ideal Point Method

Finally, to select the best compromise solution from PF_candidate, the results from the two game stages are synthesized. A two-dimensional decision space is formed by the Balance Metric and the Stability Metric. The weighted ideal point method is used to rank the solutions. The solution with the minimum weighted Euclidean distance D to the ideal point (0, 0) is selected as the final recommended strategy.

$$D_i = \sqrt{(w_s \times S_i)^2 + (w_c \times C_i)^2} \quad (4)$$

where, D_i is the comprehensive distance for scheme i; S_i and C_i are the normalized Shapley value variance and Core constraint violation for scheme i, respectively; w_s and w_c are the weights assigned to the two dimensions, representing the decision-maker's preference, where $w_s + w_c = 1$.

3 Case Study

3.1 Study Area and Model Setup

To demonstrate the application of the proposed framework, a numerical experiment was conducted on a representative two-reservoir system. This system consists of two reservoirs in series: the upstream Reservoir A and the downstream Reservoir B. The multi-objective optimization model, detailed in Section 2.1, was run for a typical impoundment period (72 days) under a normal inflow scenario. The initial and final water levels were set consistent with the historical operation to ensure a fair comparison. This process yielded an initial set of 190 Pareto-optimal solutions. After applying the hybrid screening method, a representative set of 20 candidate solutions was obtained for the subsequent game-theoretic evaluation.

To visualize the complexity of the trade-off landscape and the effectiveness of the screening process, Figure 1 illustrates the initial Pareto front in the three-dimensional objective space. It is visually evident that the initial solutions (gray dots) form a complex, non-uniform surface. The 20 candidate solutions selected by our hybrid screening method (blue triangles) are more evenly distributed across the entire front, effectively preserving the diversity of the solution set. This ensures that the subsequent game-theoretic evaluation is based on a high-quality and unbiased set of alternatives. The detailed objective values for these 20 schemes are presented in Table 1.

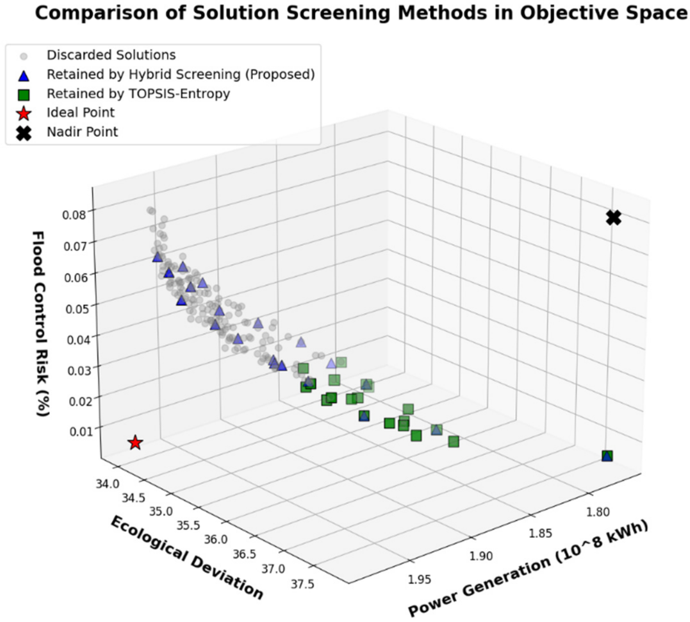


Fig. 1. Comparison of solution screening methods in the three-dimensional objective space.

Table 1. Solutions Retained by The Hybrid Screening Method

Scheme ID	Power Generation (10^8 kWh)	Ecological Deviation	Flood Risk (%)
1	1.25	17.13	0.07
2	1.36	16.09	0.12
3	1.38	15.99	0.14
4	1.39	14.86	0.21
5	1.39	16.13	0.15
6	1.37	15.32	0.13
7	1.26	14.66	0.09
8	1.35	14.83	0.14
9	1.4	15.62	0.18
10	1.34	14.5	0.16
11	1.38	15.04	0.17
12	1.21	15.47	0.06
13	1.31	14.54	0.13
14	1.39	15.38	0.16
15	1.29	14.92	0.09

16	1.34	15.06	0.11
17	1.24	16.93	0.06
18	1.33	15.51	0.09
19	1.35	15.64	0.1
20	1.3	15.25	0.08

3.2 Dual-Game Evaluation and Final Decision

The 20 candidate solutions were then evaluated using the two-stage game-theoretic framework. For each solution, two key metrics were calculated: the Shapley value variance to represent its inter-objective balance (a lower value is better), and the degree of Core constraint violation (δ) to represent its inter--stakeholder stability (a lower value is better).

To synthesize these two dimensions and select a final compromise solution, the weighted ideal point method was applied. In the absence of a priori information favoring one dimension over the other, equal weights were assigned to both balance and stability to ensure an objective and impartial evaluation. The final weighted Euclidean distance (D) to the ideal point (0, 0) was calculated for each scheme.

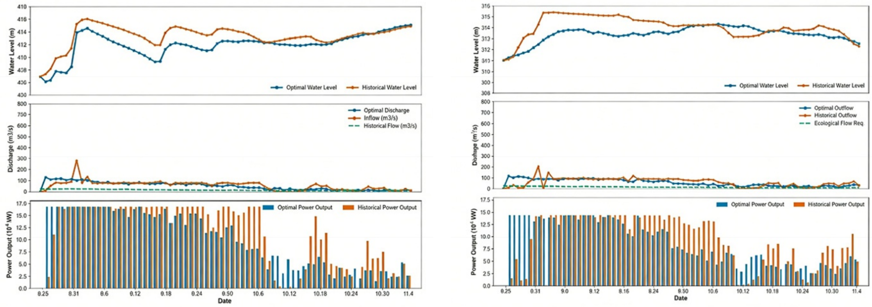
The complete evaluation and ranking results are summarized in Table 2. As shown in the table, Scheme #20 was identified as the best compromise solution, as it possesses the minimum weighted distance (D = 0.259). This scheme represents the most superior trade-off between achieving balance among objectives and ensuring stability among stakeholders under an impartial preference.

Table 2. Ranking of Comprehensive Decision Outcomes via Weighted Ideal-Point Method

Scheme ID	Shapley Variance (Balance)	Core Violation (Stability)	Normalized Balance
20	0.0075	0.4042	0.259
7	0.0076	0.4076	0.264
15	0.0040	0.4184	0.278
16	0.0060	0.4191	0.280
17	0.0045	0.4373	0.301
18	0.0024	0.4526	0.311
19	0.0193	0.3804	0.311
…	…	…	…
1	0.0559	0.4435	0.435

3.3 Performance Validation of the Optimal Scheme

Based on the comprehensive evaluation, Scheme #20 was identified as the best compromise solution. To further assess its practical value and illustrate the underlying operational logic, its detailed hydrographs were compared against the historical operation plan. Figure 2 visualizes this comparison for both the Sanliping and Siping reservoirs in the cascade.



(a) Reservoir A (b) Reservoir B

Fig. 2. Comparison of operational hydrographs for the optimal scheme (#20) and the historical plan at (a) Reservoir A and (b) Reservoir B.

The comparison highlights the intelligent trade-offs captured by our selected scheme. As depicted in Figure 2, the optimal scheme demonstrates a more sophisticated and proactive scheduling strategy. For instance, at the upstream Reservoir A (Fig. 2a), the optimal scheme maintains a lower water level before the major flood peak, effectively reserving flood control capacity. This not only significantly reduces the flood risk but also avoids the massive water spillage that occurred in the historical plan, thereby allowing for more efficient water utilization. Concurrently, the outflow process under the optimal scheme is considerably smoother and consistently remains above the ecological flow requirement (dashed green line), ensuring the ecological health of the downstream river. A similar, coordinated operational pattern is observed at the downstream Reservoir B (Fig. 2b).

Furthermore, the operational hydrographs in Figure 2 provide insights into the quality and robustness of the optimal scheme. Unlike the historical plan, which exhibited large, erratic fluctuations in both water level and outflow, Scheme #20 demonstrates a significantly smoother and more predictable operational trajectory. This smoothness is a key indicator of a high-quality solution, as it implies reduced stress on dam structures and more stable downstream hydraulic conditions. Moreover, the ability of Scheme #20 to consistently maintain outflows above the ecological requirement, even while managing flood peaks, demonstrates its robustness against intra-seasonal hydrological variability. It is not merely a single-point optimum, but a dynamically stable strategy that can better adapt to a range of conditions throughout the impoundment period.The quantitative performance comparison is detailed in Table 3. While Scheme #20 involves a calculated sacrifice, reducing total power generation by 11.8% compared to the historical benchmark, this decision unlocks overwhelming improvements in other critical areas. Specifically, it leads to a 73.4% reduction in ecological deviation and a near-complete elimination of flood risk, which plummets from 23.2% to a mere 0.08%.

This demonstrates that our framework does not simply seek optimization, but rather a holistic rebalancing of priorities. By accepting a marginal decrease in one objective, Scheme #20 achieves a disproportionately large gain in overall system safety and environmental health. Therefore, from a comprehensive perspective that values ecological integrity and public safety alongside economic benefits, Scheme #20 represents a significantly superior and more sustainable operational strategy.

Table 3. Performance comparison between the optimal scheme (#20) and the historical plan.

Scheme	Power Generation(10^8 kWh)	Ecological Deviation	Flood Risk (%)
Scheme #20	1.30	15.25	0.08
Historical	1.475	57.312	23.2

4 Conclusion

This paper addressed the challenge of multi-objective decision-making for the operation of a two-reservoir system by proposing and applying a two-stage cooperative game-theoretic framework. The framework first models the trade-offs among operational objectives as a "Target Game," evaluated by the variance of the Shapley value. It then models the interactions among stakeholders as a "Stakeholder Game, " evaluated by the degree of Core constraint violation. This approach allows for a separate assessment of inter-objective balance and inter-stakeholder stability.

The framework was successfully applied to an illustrative case of a two-reservoir system. The results indicated that the proposed methodology could effectively identify a compromise solution (Scheme #20) from a large set of Pareto-optimal alternatives. A comparative analysis showed that this selected scheme, while resulting in an 11.8% decrease in power generation, led to a 73.4% reduction in ecological deviation and a 99.7% reduction in flood risk when compared to the historical operation plan.

In conclusion, this study demonstrates a method for integrating cooperative game theory into the decision-making process for multi-objective reservoir scheduling. By quantifying and decoupling the concepts of objective balance and stakeholder stability, the framework provides a structured basis for evaluating and selecting operational strategies.

Future work could extend this research by incorporating more complex utility functions within the stakeholder game or by integrating the decision framework with real-time forecasting systems to support adaptive operational management.

Acknowledgments

We greatly thank anonymous reviewers for the good comments and suggestions on improving this manuscript. This study was funded by the Jilin Electric Power Scientific Research Institute Co. Ltd Science and Technology Project Funding: Research on Intelligent Flood Risk Warning Technology for Power Grid Equipment (2023JBGS-08), supported by the Open Research Fund of National Engineering Research Center of Water Resources Efficient Utilization and Engineering Safety: Study on the risk transfer mechanism of flood regulation for giant water engineering groups (GJGCZX-JJ-

202422), supported by the Open Research Fund of Hubei Key Laboratory of Construction and Management in Hydropower Engineering, China Three Gorges University (2024KSD20), and supported by the Major Science and Technology Project of the Ministry of Water Resources: Study on Collaborative Response Strategies to Extreme Flood Disasters in Watersheds Under a Changing Environment (SKS-2022003) , supported by the China Three Gorges University Science Fund: Research and Development of Smart Emergency Response Technology for Flood Control and Risk Avoidance (2024KTZB04), supported by the Hubei Provincial Natural Science Foundation Program General Surface Project: Research on Key Technologies of Digital Twin Emergency Risk Avoidance Platform for Hubei Provincial Flood Storage and Detention Areas (2023AFB594), supported by the Open Research Fund Project of Yangtze River Scientific Research Institute, Changjiang Water Resources Commission: Research on Flood Control Collaborative Optimization of Reservoir Group in Xiaoshui River Basin Driven by Long-series Hydrological-Hydrodynamic-Water Conservancy Project Coupled Model (CKWV2025918/KY).

References

1. YAO H Y, LI Y, ZHANG H, et al. Long-term optimal reservoir operation with tuning on large-scale multi-objective optimization: Case study of cascade reservoirs in the Upper Yellow River Basin[J]. Journal of Hydrology: Regional Studies, 2022, 40: 101000.
2. JIN J L, FU J, WEI Y M, et al. A Hierarchical Fuzzy Comprehensive Evaluation Model for Flood Risk Assessment of Reservoir Systems[J]. Water Resources Management, 2022, 36(1): 267-282.
3. WANG H, CHEN H, LIU H, et al. Selection of Water Resources Project Management Mode Using the Delphi Method and Multicriteria Decision-Making Approach[J]. Water Resources Management, 2020, 34(11): 3559-3575.
4. Zarei M, Bozorg-Haddad O, Baghban S, et al. Machine-learning algorithms for forecast-informed reservoir operation (FIRO) to reduce flood damages[J]. Scientific Reports,2021,11,(1):1-21.
5. Madani K, Hooshyar M. A game theory-reinforcement learning (GT-RL) method to develop optimal operation policies for multi-operator reservoir systems[J]. Journal of Hydrology,2014,519,(PartA):732-742.
6. NI X K, CHEN X, LI Y H, et al. A Subjective-Objective Integrated Multi-Objective Decision-Making Method for Reservoir Operation Featuring Trade-Offs Among Non-Inferior Solutions Themselves[J]. Journal of Hydrology, 2022, 613(Part A): 128430
7. ZENG, Y L, JIANG B, CAI, Y P, et al. A hybrid game theory and mathematical programming model for solving trans-boundary water conflicts[J]. Journal of Hydrology, 2019,570,666-681.
8. Wee W J, Zaini, N B, Ahmed, A N, et al. A review of models for water level forecasting based on machine learning[J]. Earth Science Informatics,2021,14,(4):1707-1728.
9. Zarei A, Mousavi S F, Gordji M E, et al. Optimal Reservoir Operation Using Bat and Particle Swarm Algorithm and Game Theory Based on Optimal Water Allocation among Consumers[J].Water Resources Management, 2019,33, (9) :3071-3093.
10. YASEEN Z M, EHTERAM M, HOSSAIN M S, et al. A novel hybrid evolutionary data-intelligence algorithm for irrigation and power production management: Application to multi-purpose reservoir systems[J]. Sustainability, 2021, 13(4): 1730.