APPLICATION OF MULTI-CRITERIA DECISION-MAKING (MCDM) TO SUPPORT EFFECTIVE FLOOD-SEASON OPERATION OF THE MULTI-RESERVOIR SYSTEM IN THE MA RIVER BASIN

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Abstract: *Flood-season operation of multi-reservoir systems requires the simultaneous consideration of multiple objectives, including dam safety, downstream flood mitigation, carryover storage for the dry season, and hydropower generation. This study integrates HEC-ResSim simulation with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to compare five operational alternatives for the Ma River Basin during the period from 1 July to 30 November 2025. The alternatives were developed by reducing the maximum pre-flood water levels at the Hua Na, Cua Dat, and Trung Son reservoirs by 0-2.0 m and were evaluated using nine quantitative criteria under eight weighting schemes representing different management priorities. The results show that the alternative involving a 2.0 m reduction in the maximum pre-flood water level provides the greatest downstream flood-mitigation effectiveness, but at the expense of reduced carryover storage for the dry season and hydropower generation. In contrast, the 0.5 m reduction alternative provides a relatively stable compromise and is more suitable when a balance among operational objectives is required. Overall, integrating MCDM with reservoir-operation simulation enables the trade-offs among competing objectives to be quantified, thereby directly supporting context-specific operational decision-making rather than prescribing a single fixed operating rule.*

Keywords: *MCDM, TOPSIS, Ma River Basin, multi-reservoir system operation.*

1. Introduction

Numerous studies have shown that flood risk is increasing under the impacts of climate change as extreme precipitation and major flood events become more frequent and intense [1]. Recent global assessments indicate that approximately 1.81 billion people, equivalent to about 23% of the world population, are directly exposed to 1-in-100-year floods [2]. Reservoir systems can substantially reduce downstream flood exposure by attenuating flood peaks when sufficient flood-control storage and appropriate operating rules are available [3], [4]. However, the effectiveness of reservoir regulation depends strongly on how flood-control requirements are balanced against other operational objectives, particularly water storage and hydropower generation.

Even for a single reservoir, multi-objective operation is inherently complex because flood control, downstream safety, water storage, and hydropower generation may conflict with one another [4]. Flood-season operation becomes substantially more challenging in multi-reservoir and cascade systems because of increasing spatial and temporal constraints, interdependence among reservoirs, and the need for coordinated operation [5], [6]. In such systems, releases from an upstream reservoir may directly affect downstream reservoirs and control points. Inadequate or uncoordinated operation may therefore increase downstream impacts and reduce overall system efficiency [7], [8]. These adverse effects can be mitigated through appropriate coordination among

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reservoirs, highlighting the importance of system-wide rather than individual-reservoir operation.

In practical reservoir management and operation, two related questions commonly arise: (i) How can feasible operational alternatives be generated while satisfying structural, hydraulic, hydrological, and operating constraints; and (ii) Among these alternatives, which one should be prioritized when conflicts arise among operational objectives and associated risks? The first question is generally addressed through reservoir simulation or optimization. The second concerns the selection of a preferred alternative from a set of feasible options and therefore requires an appropriate decision-support approach.

Multi-criteria decision-making (MCDM) provides such a framework by transforming heterogeneous performance criteria onto a comparable scale, incorporating management priorities through criterion weights, and enabling consistent comparison and ranking of alternatives [9]. In addition to reservoir-operation problems, MCDM has been applied to flood and drought risk management, water-quality management, groundwater planning, and monitoring-network design. A common feature of these applications is the need to synthesize multidimensional information and clarify trade-offs among competing objectives [10]. Many previous studies have focused on deriving optimal reservoir operation policies or operating rules through optimization-based approaches. However, practical reservoir management frequently requires the selection of a preferred alternative among multiple feasible options while considering conflicting operational objectives and different management priorities. Therefore, this study emphasizes the decision-support stage by integrating HEC-ResSim simulation outputs with TOPSIS-based ranking to compare feasible flood-season operational alternatives under different management-priority scenarios.

This approach is particularly useful when operational objectives are competing, and their relative priorities vary according to the management context. During the flood season, the most prominent conflict is often between flood control, aimed at preventing downstream inundation, and water storage [10] for other purposes or for subsequent use during the dry season. By contrast, dry-season operation generally places greater emphasis on meeting water-supply requirements and protecting ecological conditions.

2. Study Area

The Ma River Basin is one of the major river basins in North Central Viet Nam and plays an important role in water supply, agricultural production, hydropower generation, and disaster prevention and mitigation. The basin extends across the territories of Viet Nam and Laos. Within Vietnamese territory, the Ma River Basin is geographically located between 20°03’30” and 22°37’30” N and between 103°05’00” and 106°05’00” E. It is bordered by the Da River Basin to the North, the Hieu River Basin to the South, the Mekong River Basin to the West, and the Gulf of Tonkin to the East. The basin exhibits marked spatial variations in topography, ranging from mountainous upper reaches to the alluvial and coastal plains of the lower basin, which influence runoff concentration and reservoir-regulation conditions (Figure 1).

The flow regime of the Ma River Basin exhibits pronounced seasonal variability, with the flood season extending from June to October and the dry season from November to May. Annual streamflow is closely controlled by the rainfall regime, with most of the total water volume concentrated during the flood season. The largest floods on the Ma River generally occur between July and September, with the flood peak most observed in August. Overall, major floods tend to occur earlier in the upper and middle reaches of the Ma River, but later in the lower reaches and along the Chu River.

The Ma River Basin contains an extensive water-regulation infrastructure, including more than 1,500 reservoirs and over 1,000 diversion weirs. The inter-reservoir operation procedure promulgated under Decision No. 214/QĐ-TTg dated 13 February 2018 specifies the operation

of Hua Na, Dong Van, Cua Dat, Xuan Minh, Trung Son, Thanh Son, Hoi Xuan, Ba Thuoc 1, Ba Thuoc 2, and Cam Thuy 1 reservoirs. These reservoirs differ substantially in regulation capacity, operational function, and location within the river system, increasing the complexity of coordinated flood-season operation when flood mitigation, reservoir safety, water storage, and other operational objectives must be considered simultaneously.

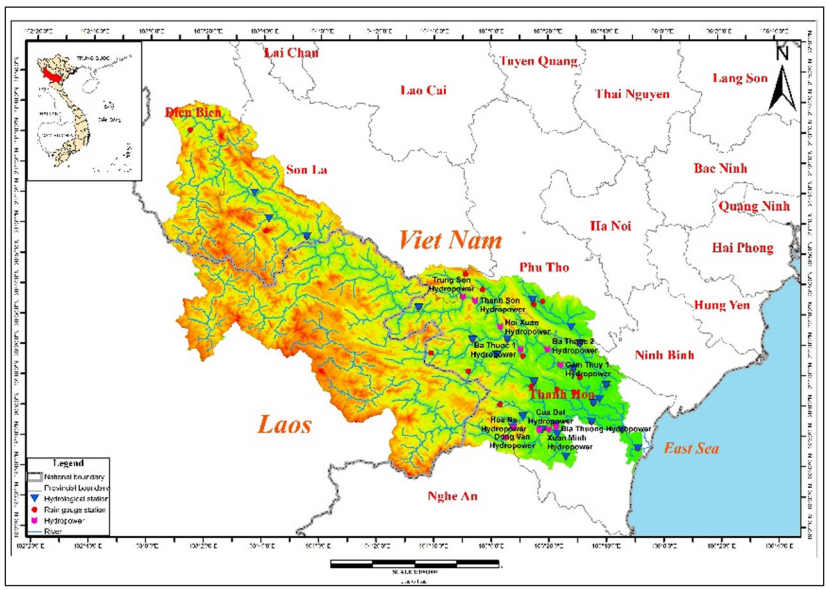


Figure 1. The Ma River Basin

3. Data and Methods

3.1. Research Methodology

This study integrates reservoir-operation simulation with a multi-criteria decision-making approach. Flood-season operational alternatives were simulated using HEC-ResSim, and the outputs were converted into quantitative criteria representing reservoir safety, downstream flood mitigation, carryover storage for the dry season, and hydropower generation. TOPSIS was then applied to normalize, aggregate, and rank the feasible alternatives under multiple weighting schemes representing different management priorities. These weighting schemes were also used to assess the sensitivity and robustness of the rankings.

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), originally proposed by Hwang and Yoon [11], ranks alternatives according to their relative distances from the positive and negative ideal solutions. For each alternative a Є A, gi(a) denotes the performance value of alternative a with respect to criterion i, where *I = 1,…,n*. The normalized criterion value γi(a) is calculated as:

$$\gamma_i(a) = \frac{g_i(a)}{\sqrt{\sum_{a \in A} [g_i(a)]^2}}$$

Where, $\gamma_i(a)$ denotes the normalized criterion value of alternative a for criterion *i*.

After normalization, the positive and negative ideal solutions are determined based on the normalized criterion values γi(a). For benefit criteria, the positive ideal corresponds to the maximum value and the negative ideal to the minimum value; for cost criteria, these definitions are reversed.

$$\gamma_i(a^+) = \max_{a \in A}\{\gamma_i(a)\}$$

$$\gamma_i(a^-) = \min_{a \in A}\{\gamma_i(a)\}, \; i = 1,\ldots,n$$

The distances from the positive and negative ideal solutions are calculated using the weighted Euclidean distance:

$$d(a, a^+) = \sqrt{\sum_{i=1}^{n}[w_i\gamma_i(a) - w_i\gamma_i(a^+)\,]^2}$$

$$d(a, a^-) = \sqrt{\sum_{i=1}^{n}[w_i\gamma_i(a) - w_i\gamma_i(a^-)\,]^2}$$

Where $w_i > 0$ denotes the weight assigned to criterion i , with $\sum_i w_i = 1$. Based on the two distance measures, the relative closeness coefficient of each alternative is calculated as:

$$V(a) = \frac{d(a,a^-)}{d(a,a^+) + d(a,a^-)}\ ,\ 0 \le V(a) \le 1$$

A larger value of *V(a)* indicates a higher-priority alternative; therefore, alternatives are ranked in descending order of *V(a)*. Because TOPSIS rankings are influenced by criterion weights, multiple weighting schemes were examined to assess ranking stability under different management priorities.

Other MCDM methods, including AHP, VIKOR, and PROMETHEE, are also widely used in water-resource decision problems [12], [13], [14]. AHP derives criterion weights through pairwise comparisons, VIKOR identifies compromise solutions by balancing overall utility and individual regret, and PROMETHEE ranks alternatives using preference-based pairwise comparisons. In contrast, this study evaluates predefined feasible reservoir-operation alternatives under different management-priority weighting schemes. TOPSIS was therefore selected because its distance-based framework provides an intuitive measure of each alternative's proximity to the desired condition and separation from the least desirable condition [15].

3.2. Development of the Evaluation Criteria and Operational Alternatives

3.2.1. Design of the Operational Alternatives

The operational alternatives were developed by adjusting the maximum pre-flood water levels at Hua Na, Cua Dat, and Trung Son, which play major regulation roles in the Ma River multi-reservoir system. These reservoirs are assigned maximum pre-flood water levels under Decision No. 214/QĐ-TTg dated 13 February 2018 [11]. Lowering these levels increases the available flood-control storage before major inflows, thereby enhancing flood-attenuation capacity, but may reduce carryover storage for the dry season and hydropower generation. Therefore, different pre-flood drawdown levels were examined to quantify these operational trade-offs. Five alternatives, S0-S4, were defined by reducing the maximum pre-flood water level by 0, 0.5, 1.0, 1.5, and 2.0 m, respectively. The target maximum pre-flood water level for reservoir i under alternative k was determined as: $Z^{(k)}_{MNCNTL,i} = Z^{(0)}_{MNCNTL,i} - \Delta Z_k$

Where: $Z^{(k)}_{MNCNTL,i}$ is the maximum pre-flood water level specified for reservoir *i* under the baseline condition, and ΔZ_k is the drawdown applied under alternative *k*.

Table 1. Design of the operational alternatives

Alternative	Reduction in the pre-flood water level	Operational significance
S0	0 m	Baseline alternative, retaining the maximum pre-flood water level specified in the operation procedure
S1	0.5 m	Slight increase in flood-control storage capacity
S2	1.0 m	Moderate increase in flood-control storage capacity
S3	1.5 m	Substantial increase in flood-control storage capacity
S4	2.0 m	Maximum flood-control storage capacity among the evaluated alternatives

All alternatives were simulated using HEC-ResSim from 1 July to 30 November 2025. Except for the maximum pre-flood water levels, reservoir inflows, operating rules under Decision No. 214/QĐ-TTg, hydraulic-structure parameters, and downstream boundary and control conditions were kept unchanged. Each alternative was screened against mandatory constraints on structural safety, permissible water levels, discharge capacity, and prescribed operating requirements. TOPSIS ranking was subsequently performed only for alternatives satisfying all mandatory constraints; therefore, differences among the ranked alternatives primarily reflect the effects of pre-flood drawdown on flood mitigation, flood-control storage, carryover storage for the dry season, and hydropower generation.

3.2.2. Principles and Method for Establishing the Evaluation Criteria

The evaluation criteria were developed based on five principles: consistency with the flood-season inter-reservoir operation procedure; quantifiability; clearly defined units and optimization directions; limited redundancy; and the ability to represent trade-offs between flood-control performance and post-flood-season water-resource utilization. Because dry-season water demand was not explicitly simulated, end-of-flood-season reservoir storage was used as a proxy for water availability entering the dry season. Accordingly, C8 represents carryover storage for the dry season through attainment of the prescribed storage target.

Table 2. Definitions, formulas, units, and optimization directions of the evaluation criteria

ID	Criterion group	Criterion name and definition	Calculation formula	Unit	Optimization direction
C1	Reservoir safety	**Maximum exceedance above the pre-flood limiting water level:** The maximum exceedance observed across all reservoirs (i) and time steps *t*; $Z_{i(t)}$ is defined as the greater of the water levels at the beginning and end of each computational time step.	$C_1 = \max_{i,t}\{[z_i(t) - z_{MNCNTL,i}(t)]^+\}$	m	Minimize
C2	Reservoir safety	**Cumulative exceedance above the pre-flood limiting water level:** An integrated measure of the magnitude and duration of exceedance above the pre-flood limit across the entire reservoir system.	$C_2 = \sum_i \sum_t [z_i(t) - z_{MNCNTL,i}(t)]^+ \Delta t$	m·day	Minimize
C3	Reservoir safety	**Occupation ratio of available flood-control storage:** The maximum proportion of the available flood-control storage occupied during operation. Storage volume (W) is determined from the reservoir elevation-storage relationship.	$C_3 = 100 \max_{i,t}\left\{\frac{[w_i(t) - w_{MNCNTL,i}(t)]^+}{\max[w_{hard,i} - w_{MNCNTL,i}(t), \varepsilon]}\right\}$	%	Minimize

ID	Criterion group	Criterion name and definition	Calculation formula	Unit	Optimization direction
C4	Down-stream flood control	**Maximum exceedance above the control water level at downstream control points:** The maximum water-level exceedance recorded at the two downstream control stations, Ly Nhan and Xuan Khanh.	$C_4 = \max_{s,t} \left\{ \left[H_s(t) - H_{gh,s} \right]^+ \right\}$	m	Minimize
C5	Down-stream flood control	**Total duration of downstream water-level exceedance above the control threshold:** The exceedance duration aggregated across all control stations using a daily computational time step. One day of exceedance at one station is counted as one station-day.	$C_5 = \sum_s \sum_t [H_s(t) > H_{gh,s}] \ \Delta t$	day-sta-tion	Minimize
C6	Down-stream flood control	**Peak routed downstream discharge at the control points:** The maximum routed discharge observed at downstream control points during the simulation period.	$C_6 = \max_{s,t} \{ Q_{routed,s}(t) \}$	m³/s	Minimize
C7	Down-stream flood control	**Maximum daily flood intensity based on downstream water-level change:** The maximum absolute day-to-day change in downstream water level, used as a daily indicator of flood intensity (Δt = 1 day).	$C_7 = \max_{s,t} \left\{ \frac{\lvert H_s(t) - H_s(t-1) \rvert}{\Delta t} \right\}$	m/ day	Minimize
C8	Carryover storage for the dry sea-son	**Attainment ratio of the carryover storage for the dry season:** The degree to which the system-wide storage target is achieved at time T; Wtarget is determined from the normal water level, whereas Wmin corresponds to the dead water level.	$C_8 = \min \left\{ 100, \max \left[0, 100 \ \frac{\sum_i (w_i(T) - w_{min,i})}{w_{taget,i} - w_{min,1}} \right] \right\}$	%	Maximize
C9	Energy benefit	**Total hydropower generation during the flood season:** The total electricity generated by the reservoir system over the simulation period.	$C_9 = \sum_i \sum_t E_i(t)$	MWh	Maximize

Nine criteria were classified into four groups: reservoir safety (C1-C3), downstream flood mitigation (C4-C7), carryover storage for the dry season (C8), and hydropower generation (C9). C1-C7 are cost criteria to be minimized, whereas C8 and C9 are benefit criteria to be maximized.

Criteria C1-C3 characterize reservoir flood-control storage. C1 represents the maximum exceedance above the pre-flood limiting water level, C2 reflects both the magnitude and duration of exceedance, and C3 expresses the maximum occupation ratio of available flood-control storage. In Equation (C3), $W_i(t)$ denotes reservoir storage of i at time t, $W_{MNCNTL,i}(t)$ is the storage corresponding to the maximum pre-flood water level, $W_{hard,i}(t)$ is the upper operational water-level storage limit, and $\varepsilon=10^{-6}$ is used to avoid numerical instability. Criteria C4-C7 characterize downstream impacts. C4 and C5 describe the magnitude and duration of exceedance above the control thresholds, respectively; C6 represents the magnitude of the routed flood peak; and C7 controls abrupt changes in water level, thereby incorporating the stability of the regulation process. Criteria C4-C7 characterize downstream flood impacts at Ly Nhan and Xuan Khanh station. C4 and C5 quantify the magnitude and duration of water-level threshold exceedance, C6 represents the peak routed discharge, and C7 reflects the maximum daily water-level change. Unlike C4, which is threshold-based, C6 represents the absolute magnitude of the routed flood peak and therefore provides complementary information on downstream flood severity. Downstream water levels were derived from routed discharges using stage-discharge relationships and compared with flood-warning thresholds. C8 evaluates attainment of the carryover-storage target to limit excessive loss of water retained for the dry season, whereas C9 represents total hydropower generation during the simulation period.

3.2.3. Development of Weighting Scenarios and Sensitivity Analysis

In MCDM, criterion weights reflect different management priorities; therefore, eight weighting schemes (W0-W7) were developed to represent alternative operational contexts: baseline weighting, integrated priorities, downstream flood-mitigation priority, reservoir flood-control storage priority, carryover-storage priority, near-equal weighting, downstream stability priority, and integrated post-flood-season water-resource utilization. Higher weights were assigned to criteria associated with the dominant objective of each scheme. These weighting schemes were used as alternative preference structures for sensitivity analysis rather than statistically derived objective weights.

W0 was used as the comparison benchmark and W1 as the primary reference scheme, whereas W2-W7 represent alternative management-priority structures. Ranking robustness was assessed by examining whether an alternative maintained a high rank across multiple weighting schemes rather than performing well under only one specific priority structure.

Table 3. Weighting schemes used in TOPSIS for sensitivity analysis

ID	W0	W1	W2	W3	W4	W5	W6	W7
C1	0.15	0.14	0.13	0.20	0.12	0.12	0.13	0.11
C2	0.10	0.08	0.07	0.14	0.07	0.11	0.08	0.07
C3	0.10	0.10	0.09	0.16	0.08	0.11	0.09	0.07
C4	0.20	0.22	0.25	0.17	0.20	0.12	0.22	0.15
C5	0.15	0.16	0.18	0.12	0.14	0.11	0.17	0.12
C6	0.10	0.08	0.09	0.08	0.08	0.11	0.08	0.08
C7	0.05	0.06	0.06	0.05	0.05	0.10	0.13	0.08
C8	0.10	0.12	0.09	0.06	0.20	0.11	0.07	0.14
C9	0.05	0.04	0.04	0.02	0.06	0.11	0.03	0.18
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

4. Results and Discussion

4.1. Evaluation of Operational Alternatives by Objective Group

The nine evaluation criteria show that no single operational alternative performs best across all objectives. The main trade-off occurs between maintaining flood-control storage and mitigating downstream impacts, on the one hand, and preserving carryover storage for the dry season and hydropower generation, on the other.

The baseline alternative S0 performs favorably for C8 and C9 because it retains the maximum pre-flood water levels specified in the current operating procedure, thereby preserving storage and hydraulic head. However, it provides no additional flood-control storage and therefore offers less improvement in downstream flood-mitigation performance. By contrast, S4, corresponding to a 2.0 m reduction in the maximum pre-flood water level, provides the greatest additional flood-control storage and performs particularly well for C4, C5, and C7. The larger initial storage space enables greater retention of flood inflows, thereby reducing downstream threshold exceedance and water-level fluctuations. However, these benefits are accompanied by poorer performance for C8 and C9, indicating a clear trade-off with carryover storage and hydropower generation. Alternative S1, with a 0.5 m reduction, maintains relatively balanced performance across the objective groups. It provides additional flood-control storage compared with S0 while causing smaller reductions in carryover storage and hydropower generation than S4, thereby representing a moderate compromise between flood mitigation and post-flood-season water and energy benefits.

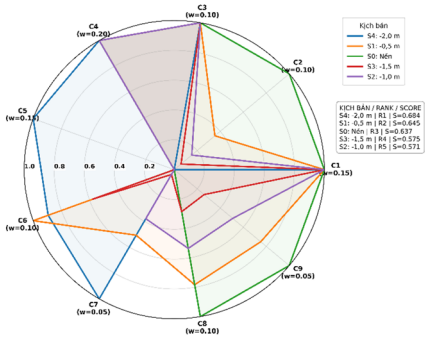
The results for S2 and S3 further indicate that overall performance does not vary monotonically with the magnitude of pre-flood drawdown. Increasing the drawdown alters not only available flood-control storage but also the timing, magnitude, and coordination of reservoir releases. Consequently, alternative performance depends jointly on initial reservoir conditions, inflow dynamics, operating rules, and downstream flow-routing processes. This confirms that the preferred drawdown level should be determined through simultaneous evaluation of all operational objectives.

Figure 2 shows only limited changes in the radar-chart shapes across weighting schemes because the underlying normalized criterion values are derived from the same HEC-ResSim outputs, while only the criterion weights vary. Consequently, the radar charts illustrate how the performance profiles of the alternatives are reweighted under different management priorities, whereas the resulting preference changes are more directly reflected in the TOPSIS scores and rankings.

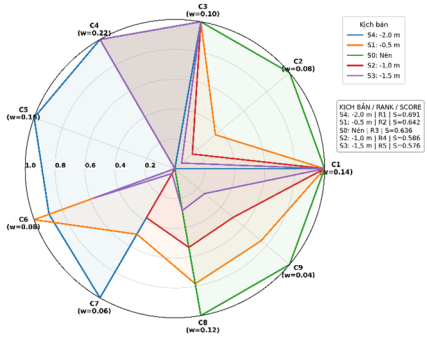
4.2. Sensitivity and Robustness of the TOPSIS Rankings

The TOPSIS rankings vary with the weighting structure. S4 ranks first under W0, W1, W2, and W6, which emphasize downstream flood mitigation and flow stability, whereas S0 ranks first under W3, W4, and W7, which place greater emphasis on reservoir safety, carryover storage, and hydropower generation. Under the near-equal weighting scheme W5, S1 achieves the highest ranking. These results confirm that the preferred alternative depends on the management priorities represented by the criterion weights.

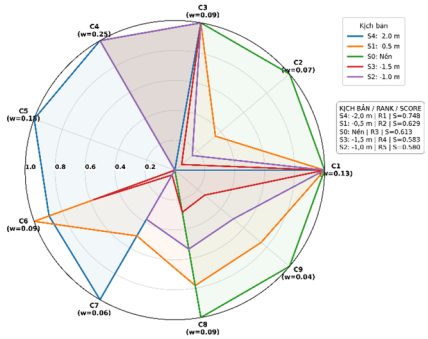
Figure 3 presents the TOPSIS ranking matrix for the operational alternatives (S0-S4) under eight weighting schemes (W0-W7). Here, R1-R5 denote ranking positions from Rank 1 to Rank 5, with R1 representing the highest priority and R5 the lowest. The ranking matrix shows that the main competition occurs among S0, S1, and S4, whereas S2 generally occupies an intermediate position and S3 remains in the lower-ranking group. The 1.0 m and 1.5 m drawdown alternatives do not provide a clear overall advantage because they achieve neither the storage and hydropower benefits of S0-S1 nor the downstream flood-mitigation performance of S4. The TOPSIS scores of S0 and S1 remain close under storage- and energy-oriented weighting schemes, with differences of only 0.009 under W4 (0.673 versus 0.664) and 0.005 under W7 (0.665 versus 0.660), indicating that S1 maintains performance close to the baseline while providing additional flood-control storage.



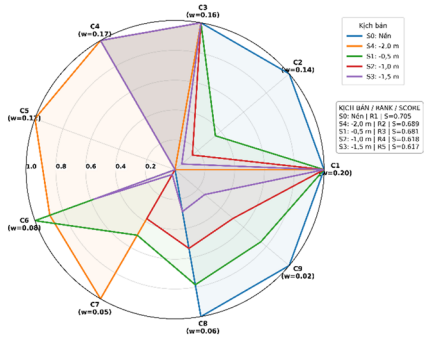
a) W0 - Baseline weighting scheme



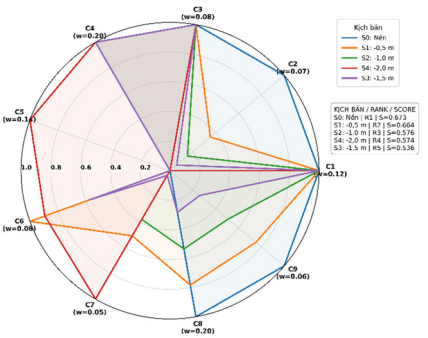
b) W1 - Integrated operational-priority weighting scheme



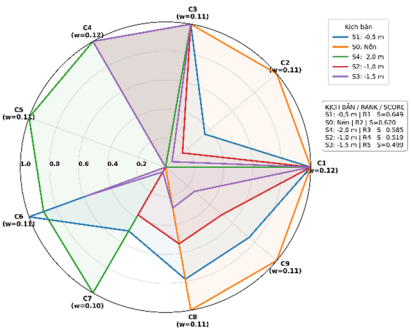
c) W2 - Downstream flood-mitigation priority



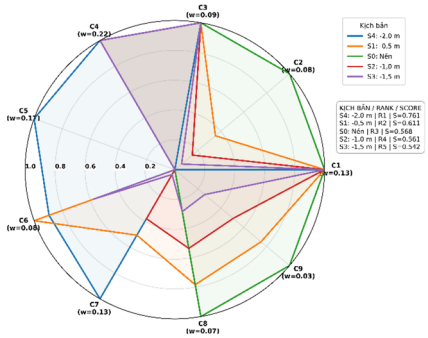
d) W3 - Reservoir safety and flood-control storage priority



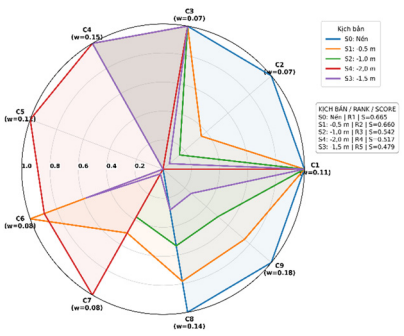
e) W4 - Dry-season carryover storage priority



f) W5 - Near-equal weighting scheme



g) W6 - Downstream flow-stability priority



h) W7 - Balance between dry-season carryover storage and hydropower generation

Figure 2. Radar charts of the weighted normalized criterion values for the operational alternatives under eight weighting schemes

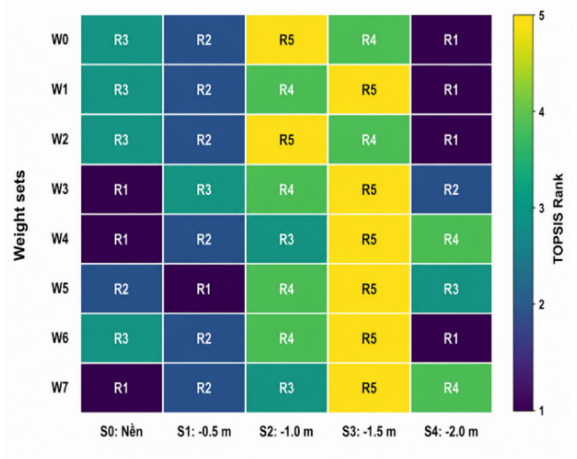


Figure 3. TOPSIS-based ranking matrix of the operational alternatives across eight weighting schemes

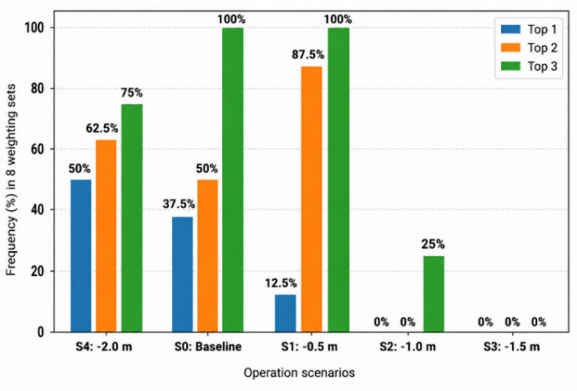


Figure 4. Frequency of the operational alternatives ranked in the Top 1, Top 2, and Top 3 across eight weighting schemes

The frequency analysis in Figure 4 further evaluates the robustness of the rankings. S4 has the highest frequency of first-place rankings (50%), mainly under weighting schemes prioritizing downstream flood mitigation. Although S1 ranks first in only 12.5% of cases, it appears in the Top 2 under 87.5% of the weighting schemes and remains within the Top 3 in all cases. Therefore, S4 provides the strongest performance when flood mitigation is the dominant objective, whereas S1 demonstrates greater ranking stability and represents a robust compromise alternative under varying management priorities.

4.3. Selection of Operational Alternatives under Different Management Priorities

The results indicate that no single alternative is optimal across all operational objectives. S4 performs favorably under weighting scenarios that emphasize flood mitigation and downstream flow stability; S0 is preferred when dry-season carryover storage and hydropower generation are prioritized; whereas S1 maintains a relatively high and stable ranking across different weighting structures, thereby exhibiting the characteristics of a compromise alternative. Accordingly, the ranking results should be used to support alternative selection under specific management-priority contexts rather than interpreted as a fixed operating rule.

TOPSIS was applied only after the simulation and feasibility-screening stages; therefore, the results reflect differences exclusively among alternatives that satisfy the prescribed safety constraints. Because the present study considers only the 2025 flood season and a predefined set of scenarios, further validation across multiple

flood events and explicit consideration of inflow uncertainty are required before the approach can be extended to practical reservoir operation.

5. Conclusions

This study integrated HEC-ResSim simulation with TOPSIS to evaluate flood-season operational alternatives for the Ma River multi-reservoir system. Five alternatives with different maximum pre-flood water levels at Hua Na, Cua Dat, and Trung Son reservoirs were assessed using nine criteria representing reservoir safety, downstream flood mitigation, carryover storage for the dry season, and hydropower generation under eight weighting schemes.

The results demonstrate that operational preferences depend on management priorities. The 2.0 m drawdown alternative (S4) provides the strongest downstream flood-mitigation performance but reduces carryover storage and hydropower benefits. The 0.5 m drawdown alternative (S1) does not always rank first but maintains stable performance across weighting schemes and represents a robust compromise solution. Therefore, the proposed framework supports priority-based selection of feasible operational alternatives rather than prescribing a single universal operating rule.

The main contribution of this study is the integration of reservoir simulation outputs with MCDM to quantitatively evaluate trade-offs among competing operational objectives. Further validation using multiple flood events and consideration of inflow uncertainty are required to assess the broader applicability of the framework.

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