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Sustainable Port Site Selection in Mountainous Areas Within Continuous Dam Zones: A Multi-Criteria Decision-Making Framework

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Abstract

The development of large-scale cascade hydropower complexes has improved the navigation conditions of mountainous rivers but creates unique "continuous dam zones," presenting complex challenges for port site selection due to hydrological variability and geological risks. To address the lack of specialized evaluation tools for this specific context, this paper constructs a comprehensive evaluation indicator system tailored for mountainous reservoir areas. The proposed system explicitly integrates critical engineering and physical constraints—specifically fluctuating backwater zones, geological hazards, and dam-bypass mileage—alongside ecological and social requirements. The Analytic Hierarchy Process (AHP) and Entropy Weight Method (EWM) are integrated using a Game Theory model to determine combined weights, and the Evaluation based on Distance from Average Solution (EDAS) model is applied to rank the alternatives. An empirical analysis of the Xiluodu Reservoir area on the Jinsha River demonstrates that operational efficiency, geological safety, and environmental feasibility constitute the critical decision-making factors. The results indicate that Option C (Majiaheba site) offers the optimal solution (ASi = 0.9695), effectively balancing engineering utility with environmental protection. Sensitivity analysis further validates the consistency and stability of this ranking under different decision-making scenarios. The findings provide quantitative decision support for project implementation and offer a replicable reference for infrastructure planning in similar complex mountainous river basins.

Keywords: mountainous port; port site selection; continuous dam area; combination weighting; EDAS; comprehensive evaluation framework

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1. Introduction

With the extensive development of global hydropower resources, the continuous construction of multiple dams for cascade development along rivers has become a prevalent engineering paradigm. This mode creates a distinct composite geographical unit known as a "continuous dam area." Its defining characteristic is the transformation of original natural rivers into a series of deep-water reservoirs that are separated by dams yet adjoin to one another end-to-end. This formation results in "segmented" waterways (resembling a lotus root) that possess superior navigation conditions within each section but are physically

isolated from one another. This phenomenon is observable in rivers with abundant hydropower resources worldwide. For instance, the main stem of the Tennessee River in the United States has achieved canalization over a 1050 km waterway from the river mouth to Knoxville following the construction of 9 cascades and 13 ship locks, supporting the annual navigation of 34,000 vessels [1]. Similarly, the Danube River, a vital water transport artery in Europe, has been developed with numerous dams equipped with ship locks, forming multiple continuous navigable reservoir sections that constitute a transnational shipping corridor [2]. In China, cascade developments such as the Three Gorges Dam and Gezhouba Dam on the mainstream of the Yangtze River have likewise realized the dual benefits of inland navigation and power generation through navigation facilities like ship locks and ship lifts [3,4].

In China, the Yangtze River Economic Belt serves as a crucial national strategy, and its development relies heavily on fully leveraging the functions of the Yangtze River's "golden waterway." The Jinsha River, constituting the upper reaches of the Yangtze, is located in the strategic hinterland of Southwest China. It serves as a critical link supporting the Western Development Strategy in the New Era and serving the development of the Yangtze River Economic Belt. In recent years, with the full completion of four world-class giant hydropower complexes (high dams)—Xiangjiaba, Xiluodu, Baihetan, and Wudongde—the lower Jinsha River has formed the world's largest "continuous dam area." The precipitous V-shaped canyon channels have been transformed into a series of deep-water navigation channels capable of accommodating 3000- to 5000-ton vessels year-round, creating unprecedented historical opportunities for extending shipping into China's western hinterland. The realization of these major projects has laid a solid foundation for breaking the navigation "bottlenecks" of the upper Yangtze River and achieving direct river-to-sea access for bulk materials from regions such as Yunnan, Guizhou, and Sichuan. This holds profound strategic significance for promoting resource development and socio-economic progress in the western region [5].

However, due to historical limitations, the development and utilization of navigation resources were not accorded due priority during the hydropower development of the Jinsha River. Among the four major hydropower complexes, except for Xiangjiaba, which is equipped with a small-scale ship lift, none were synchronously constructed with navigation structures. This ultimately resulted in four discontinuous, "segmented" waterways [6]. This status quo has led to the ineffective utilization of the scarce and high-quality navigation resources of the lower Jinsha River, physically severing upstream and downstream navigation. With regional economic development, the demand for water transport has seen a surge. The dam-bypass transport volume at Xiangjiaba has stabilized at the ten-million-ton level for years. The transportation system is currently operating at saturation, with severe issues of vessel backlog and congestion [6]. Therefore, constructing efficient dam-bypass transshipment facilities to bridge these navigation "breakpoints" has become an urgent need and a core task to transform the navigation potential of the Jinsha River into tangible benefits.

Dam-bypass ports (also referred to as transshipment terminals) constitute the core component of these facilities. They function as critical physical nodes bridging the reservoir waterways upstream of the dam with the land (or waterway) transport corridors downstream, facilitating the efficient intermodal transfer of cargo via "water-land-water" or "water-land" modes. The rationality of site selection and the rationality of the layout directly determine the overall operational efficiency and service level of the dam-bypass transshipment system. However, the deeply incised canyon reaches of the lower Jinsha River are characterized by precipitous bank slopes, complex geological structures, and a fragile ecological environment. Furthermore, the reservoir area experiences drastic water

level fluctuations influenced by the operational scheduling of the hydropower complex. Therefore, conducting systematic site selection for these dam-bypass ports within such a challenging mountainous environment—facing frequent geological hazards and strict engineering constraints—has become a complex challenge of significant practical value. Concurrently, the strict ecological protection requirements of the Yangtze River Economic Belt necessitate that environmental considerations be integrated into the lifecycle of port infrastructure from the very outset—the site selection phase. However, a significant methodological gap remains. Although MCDM methods like AHP are widely applied in port planning, the EDAS model—which excels at handling data with extreme values—has rarely been utilized in port site selection. Furthermore, existing evaluation frameworks often lack specific mechanisms to adequately address the unique engineering constraints of 'continuous dam zones,' such as drastic water level fluctuations. Therefore, this study does not aim to propose a new mathematical algorithm, but rather to construct a domain-specific decision framework that enhances the reliability and precision of site selection under these complex constraints. This study addresses this gap by taking the Xiluodu Reservoir area in the lower Jinsha River as a case study. It aims to provide decision support tools for port site selection in mountainous rivers by constructing a systematic evaluation framework. Through the comprehensive analysis of diverse influencing factors—ranging from transshipment efficiency and geological stability to ecological red lines—this study builds a multi-dimensional indicator system. This structure ensures a comprehensive assessment: it prioritizes not only operational efficiency and geological safety but also strictly accounts for ecological integrity and social impacts as critical boundary conditions for engineering decision-making.

The remainder of this paper is organized as follows: Section 2 provides a review of relevant literature. Section 3 constructs a comprehensive evaluation indicator system for port site selection, grounded in an in-depth identification of key influencing factors specific to mountainous ports. Section 4 elaborates on the methodology, incorporating Game Theory for combination weighting and applying the EDAS model for alternative optimization. Section 5 presents an empirical analysis using the site selection of the dam-bypass port upstream of the Xiluodu Hydropower Station as a case study, followed by a discussion of the evaluation results. Finally, Section 6 summarizes the study, presenting the research conclusions and recommendations.

2. Literature Review

2.1. Factors Influencing Port Site Selection in Mountainous Continuous Dam Areas

Given that research explicitly targeting port site selection within the specific environment of 'mountainous continuous dam areas' remains relatively scarce, this paper broadens the scope of the literature review. To establish a robust theoretical foundation, we draw upon studies concerning general port site selection and functionally specific ports, aiming to distill universal evaluation criteria adaptable to this study. As port site selection is a classic Multi-Criteria Decision-Making (MCDM) problem, this section reviews the literature across various port types to identify increasingly comprehensive and diversified influencing factors. Research priorities vary significantly depending on the port type. For safety-critical infrastructure, Yang et al. [7] identified 'policies and regulations' as decisive criteria for LNG terminals. In the context of tourism-oriented ports, Lin [8] highlighted the connectivity between the port and the city for the Qingdao cruise terminal. From the perspective of multimodal transport, Kou [9] prioritized the seamless integration with railway networks as a core consideration for ferry terminals. Moreover, research focusing on specific natural environments, such as seasonally frozen rivers, has established characteristics of drift ice and ice protection measures as essential factors for site selection [10].

Collectively, these studies demonstrate that modern port site selection has evolved beyond a mere engineering problem into a complex systems engineering project. It requires multi-dimensional considerations tailored to specific functional positioning and geographic contexts. Regarding the factors influencing port site selection in mountainous areas, existing research has similarly expanded across multiple dimensions. Some studies approach this from the perspective of macro-functional matching. For instance, Yan [11] proposed that site selection for terminals near hydropower complexes should balance the complex's overall functions with the terminal's specific operational role and expected economic benefits. Expanding to a broader regional scope, other scholars have proposed the theory of "regional complexes," suggesting that adjacent ports serving the same mixed hinterland should be planned systematically as a whole. This approach clarifies the functional division between central hub ports and specialized ports to avoid redundant construction [12]. Beyond functional planning, physical constraints impose distinct challenges in mountainous regions. The 'significant water level fluctuation' resulting from reservoir impoundment has emerged as a critical engineering bottleneck [13]. Addressing these hydraulic constraints, Du [14] incorporated transportation convenience and environmental feasibility into the decision matrix, while Yu [15] emphasized that river reaches with stable flow regimes should be prioritized. Additionally, factors such as the current status of the waterway, conformity with urban and rural planning, the adequacy of external supporting facilities, and geological conditions are also regarded as important common factors influencing inland terminal site selection decisions [16].

2.2. Port Site Selection Evaluation Methods

As research has progressed, scholars have explored various methodologies for evaluating port site selection. However, studies specifically focusing on ports along mountainous rivers remain relatively scarce. Regarding innovations in constructing indicator frameworks, Liu et al. [17] creatively categorized influencing factors into two types: 'abrupt-type' hard constraints (which must be met) and 'gradual-type' optimization indicators (which determine the quality of the option). Based on this classification, they built a quantitative, comprehensive evaluation model. For port layout on modernized inland waterways, Wiśnicki et al. [18] proposed a systematic "nodes first, ports second" decision-making approach. This involves first determining the hierarchy of "transport nodes" through a macro-analysis of hinterlands at different levels (e.g., long-distance vs. short-distance) and then conducting a micro-level assessment of specific sites within those nodes. In terms of specific quantitative evaluation models, scholars have focused on developing various combined evaluation models. For instance, Li [19] was among the first to apply Grey Relational Analysis (GRA) to port site ranking. Zhou [20] proposed combining the Analytic Hierarchy Process (AHP) with GRA. This method first determines subjective weights using AHP and then utilizes the GRA model to rank the alternatives. Building on this, Liu et al. [21] introduced the Entropy Weight Method (EWM) alongside AHP to calculate objective weights. They constructed a decision model that combines subjective and objective weights to achieve more scientific evaluation results. Additionally, Xiao et al. [22] proposed a purely objective evaluation model. This method utilizes EWM to determine weights based on the dispersion of data, combined with the TOPSIS model to rank the alternatives.

Given the limited methodological research specifically targeting mountainous river port site selection, this study expands its research perspective to logistics nodes with similar functions, such as dry ports. As critical hubs connecting inland hinterlands with seaports, dry ports share strong functional comparability with mountainous dam-bypass ports. For instance, Tadić et al. [23] developed a hybrid MCDM model incorporating Grey theory to better address data uncertainty. Liang et al. [24] applied the Best-Worst Method (BWM) to

dry port site evaluation, achieving more reliable weights and ranking results. Furthermore, other scholars have applied the Analytic Network Process (ANP) to dry port selection to account for the interdependence and feedback relationships among indicators [25].

2.3. Summary and Research Gap

Current research predominantly focuses on conventional coastal ports (e.g., cruise and LNG terminals) or inland dry ports. However, studies specifically addressing port site selection in mountainous rivers—particularly within the unique and complex environment of "continuous dam areas" subjected to significant artificial intervention, such as the lower Jinsha River—remain scarce. Furthermore, existing evaluation indicators often fail to adequately address the unique engineering challenges (e.g., significant water level fluctuations) and core functional positioning (e.g., dam-bypass transshipment efficiency) associated with these specific contexts. In light of this, this study aims to construct a comprehensive evaluation framework specifically tailored for mountainous port site selection and conduct an empirical analysis using the Xiluodu Reservoir area in the lower Jinsha River as a case study. The main contributions of this work include: (1) constructing an evaluation indicator system that reflects the unique characteristics of mountainous port site selection; (2) determining subjective weights via the AHP and objective weights via the EWM, while introducing a Game Theory model to derive optimal combined weights, thereby overcoming the limitations of single weighting methods; and (3) applying the Evaluation based on Distance from Average Solution (EDAS) model to rank the alternatives and conducting a sensitivity analysis to verify the robustness of the results.

3. Construction of Evaluation Indicator System for Mountainous Port Site Selection

3.1. Identification of Factors Influencing Mountainous Port Site Selection

Site selection for dam-bypass ports in the lower Jinsha River is a complex decision-making process characterized by the interplay of multiple factors, including the steep terrain of high mountain gorges, dynamic hydrology subjected to intense artificial intervention, and regional economic development demands. Therefore, the identification of influencing factors must fully account for the unique characteristics of this region. Drawing upon common practices in existing port site selection research, complex site selection problems are typically decomposed into multiple dimensions for assessment. For instance, in the context of cruise terminal site selection, scholars have constructed evaluation indicator systems spanning multiple levels, such as water conditions, land conditions, transportation, economy, and policy [26]. Based on this approach and combined with the specific characteristics of the research object, this paper identifies influencing factors across four dimensions: natural conditions, engineering technology, socio-economics, and environmental protection.

3.1.1. Natural Condition Factors

(1) Water Conditions

Port sites should be prioritized in river reaches characterized by stable flow and straight channels to minimize maneuvering difficulties for vessels during entry, exit, berthing, and unberthing operations. Specifically, the evaluation should focus on:

① Channel Morphology and Flow Regime: As emphasized in the siting practices of numerous riverside hub projects, locating terminal facilities within straight river reaches is a critical prerequisite for ensuring favorable "flow regimes" and optimizing hydraulic conditions [27]. Since mountainous rivers often exhibit high flow velocities due to steep

gradients, sites must avoid rapids, whirlpools, and hazardous shoals to ensure current speeds remain within safe navigable limits.

② Navigable Water Depth: The port must guarantee sufficient navigable depth at the terminal frontage under the design low water level to accommodate the fully loaded draft of the representative vessel type with adequate under-keel clearance.

③ Channel Width and Turning Space: Channel width in mountainous canyons constitutes another limiting factor. The port area must not only meet general navigation standards but also provide sufficient turning basins for large vessels (e.g., the 3000-ton class). Consequently, evaluating the actual available channel width at the proposed site is crucial. Crucially, the 'Fluctuating Backwater Zone' serves as a pivotal constraint in site selection. Unlike the relatively stable Perennial Backwater Zone, this area experiences drastic daily water level amplitudes and complex flow regimes driven by the dam's peak-shaving operations. Siting a terminal within this zone significantly complicates vessel maneuvering and compromises the stability of hydraulic structures. Therefore, avoiding this zone is prioritized, and it is incorporated as a key Cost-type indicator (C15) to ensure operational safety.

(2) Land Conditions

The quality of land conditions directly dictates the safety, stability, and construction cost of port engineering. In mountainous regions characterized by precipitous terrain, complex geological structures, and frequent heavy rainfall, the significance of these conditions is particularly pronounced. Evaluating land conditions requires a focused assessment of several key aspects:

① Geological Hazard Risks: Sites must strictly avoid areas with potential or historical major geological hazards such as landslides, collapses, and debris flows. Furthermore, sites should be located away from active fault zones, with full consideration given to the impact of regional seismic activity.

② Natural Bank Slope Stability: The stability status of the natural bank slope correlates directly with the long-term stability of the slopes formed post-excavation.

③ Availability of Flat Land and Shoreline: In mountainous valley terrains, the availability of flat land serves as a critical constraint. The available land width determines the feasibility of rational layouts for storage yards and roads, while the usable shoreline length is even more critical, as it directly constrains the potential number of berths and the ultimate scale of the port.

3.1.2. Engineering Technology Factors

(1) Collection and Distribution Conditions

Effective collection and distribution are paramount for dam-bypass efficiency. Site selection must prioritize locations with cost-effective access to high-grade highway networks. Site selection should prioritize locations capable of convenient and cost-effective access to high-grade highway or railway networks. Within the context of mountainous cascade hydropower complexes, the evaluation must focus on two key quantitative dimensions:

① Dam-bypass Transshipment Efficiency: For dam-bypass ports, "dam-bypass transport" constitutes the core functional component. The road transshipment distance for dam bypass directly dictates the efficiency and operational costs of transferring cargo between the upstream reservoir and downstream channels. Consequently, any alternative that significantly shortens this distance possesses a distinct economic advantage. From a sustainable perspective, minimizing the transshipment distance also directly reduces fuel consumption and greenhouse gas (GHG) emissions during the heavy-duty trucking process, contributing to the development of low-carbon green logistics.

② External Connectivity and Engineering Feasibility: Connecting the port to existing regional highway trunk lines is essential for serving the economic hinterland. In mountainous regions characterized by complex terrain, the construction length of connecting access roads directly reflects the initial engineering difficulty and investment scale required for integration into the external road network. Convenient and economical access to external trunk roads is a critical factor in reducing both port construction costs and overall regional logistics costs.

Therefore, the evaluation must balance the intrinsic efficiency of dam-bypass transshipment with the engineering feasibility and economic viability of accessing external networks.

(2) Port Construction Conditions

The engineering feasibility, cost, and construction duration of a port are intrinsically linked to the site's construction conditions and supporting facilities. Since detailed monetary estimates are often unavailable during the preliminary site selection phase, physical indicators such as the length of access roads and the difficulty of hydraulic structure construction serve as effective proxies for evaluating the relative construction costs of different alternatives. In mountainous regions characterized by complex topography, this manifests in three primary aspects:

① Difficulty of Berth Hydraulic Structure Construction: This refers to the complexity of constructing the terminal frontage structure. Mountainous rivers, particularly within reservoir areas, present the unique challenge of "significant water level fluctuations." Consequently, the selection of the hydraulic structure type—whether high-pile beam-slab, gravity-based, or floating terminal—along with the complexity of executing underwater foundation works on steep rocky substrates, serves as a critical technical determinant of construction feasibility and cost.

② Land Bearing Capacity: This pertains to the construction conditions of the land area behind the terminal (landside works). Storage yards, roads, and heavy handling machinery within the port area necessitate foundations with high bearing capacity. However, in mountainous settings, suitable land is rarely naturally available and often requires "land creation" through extensive "cut-and-fill" operations. Therefore, ensuring that the bearing capacity characteristic values—whether of natural ground or artificial fill—meet design requirements constitutes a significant engineering challenge.

③ Conditions for Accessing Supporting Facilities: The normal operation of a port is contingent upon stable and reliable infrastructure support, including water supply, power supply, and telecommunications. In remote mountainous locations, extending these utility lines to the port site often involves overcoming obstacles such as long distances and complex terrain. Consequently, the convenience and engineering cost of such access are essential engineering technology factors that must be weighed in the site selection decision.

3.1.3. Socio-Economic Factors

(1) Economic Benefits

① Economic Hinterland and Cargo Sources: As fundamental infrastructure serving the regional economy, the survival and development of a port are predicated on the support of stable and sufficient cargo sources. Consequently, site selection decisions must be grounded in a profound analysis of the economic hinterland, prioritizing locations capable of directly serving large-scale industrial and mining enterprises, energy bases, industrial clusters, or commercial agricultural production areas. Quantitatively assessing the potential cargo volume that each alternative site can attract based on its geographic location serves as a critical basis for determining its functional positioning, construction scale, and overall project feasibility.

② Long-term Development Potential: A successful site selection strategy must possess foresight. Given the substantial investment and extended lifecycle associated with port construction, the selection phase must look towards the long term. It is essential to evaluate whether the site vicinity possesses sufficient shoreline and land resources to reserve space for potential expansion or functional upgrades driven by future economic growth [28]. This consideration reflects the project's capacity for sustainable development, preventing the port from becoming a developmental bottleneck in the future due to "inherent deficiencies" (e.g., lack of expansion space).

(2) Social Impacts

① Impact on Adjacent Residential Areas: Site selection must rigorously assess whether the proposed location is proximal to significant population clusters (e.g., villages, urban built-up areas) or sensitive environmental receptors such as schools. Proximity to residential areas typically implies heightened potential for negative social externalities—such as noise, dust, and traffic congestion—as well as increased complexity in land acquisition, demolition, and resettlement. These factors may significantly escalate social resistance to project implementation.

②Occupation of Arable Land and Homesteads: In mountainous regions, flat land resources—particularly arable land—are exceptionally scarce and valuable. If port construction necessitates the occupation of arable land (especially permanent basic farmland) or numerous homesteads, it will not only substantially increase resettlement costs but may also infringe upon land protection "red lines," potentially triggering complex social conflicts. Therefore, the occupation of these scarce land resources must be a critical evaluation criterion. Therefore, minimizing the occupation of arable land is crucial for preserving scarce land resources in mountainous regions. This approach ensures that infrastructure development does not conflict with local food security, thereby reducing potential social friction.

③ Difficulty of Cross-Regional Coordination: Many large rivers, especially in mountainous areas, often serve as administrative boundaries (e.g., county or provincial borders). Siting a port on such boundary rivers is not merely a unilateral engineering decision; it necessitates complex coordination with administrative bodies on the opposite bank regarding waterway management, environmental protection, and economic synergy.

3.1.4. Environmental Protection

(1) Ecological Constraints

① Ecological Red Line Constraints: Ecological protection constitutes an inviolable "red line." Port site selection must strictly adhere to relevant laws and regulations, ensuring the absolute avoidance of statutorily designated ecologically sensitive areas. These include Tier I and II drinking water source protection areas, the core and buffer zones of nature reserves, scenic spots (landscape protection areas), national aquatic germplasm resource conservation areas, and significant cultural heritage sites. Conducting a comprehensive preliminary environmental impact assessment during the selection phase is a mandatory procedure for modern engineering construction.

② Ecological Vulnerability and Vegetation Impact: Even outside the ecological red lines, the mountainous ecosystem often exhibits significant fragility. Large-scale port construction, particularly activities involving extensive earthwork excavation and slope reinforcement, inevitably causes disturbance and degradation to the original landforms and vegetation cover. Therefore, it is imperative to assess the ecological vulnerability of the proposed site, as well as the potential impacts of construction and operation on vegetation recovery and soil and water conservation.

③Construction Conditions for Environmental Protection Facilities: Port operations inevitably generate wastewater and ship-generated waste. In mountainous valley zones character-

ized by constrained terrain, it is crucial to assess in advance whether sufficient land space is available for constructing necessary supporting environmental facilities (e.g., sewage treatment plants, waste transfer stations). Lack of suitable conditions for such facilities could lead to inadequate pollutant treatment, posing a risk of secondary pollution to the reservoir water body.

3.2. Construction of the Comprehensive Evaluation Indicator System for Mountainous Port Site Selection

Building upon the identification and analysis of various factors influencing port site selection in the mountainous lower Jinsha River, and referring to the relevant provisions on terminal siting in the General Design Code for River Port Engineering (JTS 166-2020) [29], this paper constructs a comprehensive and rational evaluation indicator system. The construction of this system adheres to the principles of systematic organization, hierarchical structure, and targeted applicability. It aims to encompass the critical links affecting site selection decisions while accurately reflecting the unique environmental conditions and engineering requirements of the reservoir area in the lower Jinsha River.

This study decomposes the site selection problem into four primary criteria: Natural Conditions, Engineering Technology, Socio-economic Benefits, and Environmental Protection. These are further refined into a series of core evaluation indicators. The detailed structure of the evaluation indicator system is presented in Table 1.

Table 1. Comprehensive Evaluation Indicator System for Mountainous Port Site Selection.

Primary Criterion (Level 1)	Secondary Criterion (Level 2)	Code	Indicator (Level 3)	Description	Type
Natural Conditions (B1)	Water Conditions	C11	Channel Flow Velocity (m/s)	Evaluates the regular flow velocity in the port area during non-flood and non-peak-shaving periods.	Cost
		C12	Water Depth at Terminal Frontage (m)	Evaluates the actual water depth at the terminal frontage under the design low water level.	Benefit
		C13	Channel Width (m)	Evaluates the navigable width of the river channel to ensure sufficient space for vessel turning and operations.	Benefit
		C14	Water Level Fluctuation Amplitude (m)	Evaluates the maximum daily water level fluctuation caused by dam peak-shaving operations.	Cost
		C15	Impact of Fluctuating Backwater Zone (0/1)	Determines whether the site is located within the hydrologically complex "fluctuating backwater zone."	Cost
	Land Conditions	C21	Seismic Fortification Intensity	The statutory seismic design standard for the region determines the required earthquake resistance level. (Degree)	Cost
		C22	Frequency of Geological Hazards (Freq/Year)	The relative annual frequency of landslides, collapses, or debris flows in the site vicinity.	Cost
		C23	Bank Slope Angle (Ratio)	The steepness of the natural bank slope; a smaller slope ratio indicates better stability.	Cost
		C24	Available Land Width (Depth) (m)	The average depth of flat land available behind the terminal for yard and facility construction.	Benefit
		C25	Usable Shoreline Length (m)	The total continuous length of shoreline suitable for berth layout.	Benefit
Engineering Technology (B2)	Collection and Distribution Conditions	C31	Road Transshipment Distance for Dam Bypass (km)	The shortest road transport distance from the upstream port to the corresponding downstream reception point.	Cost
		C32	Construction Length of Connecting Access Roads (km)	The length of new or reconstructed roads required to connect the port to the existing regional highway network.	Cost
	Port Construction Conditions	C41	Difficulty of Berth Hydraulic Structure Construction	Evaluates the engineering difficulty of constructing frontage structures (e.g., piles, pontoons).	Benefit
		C42	Conditions for Accessing Supporting Facilities	Evaluates the convenience of accessing water, power, and telecommunication infrastructure.	Benefit
		C43	Land Bearing Capacity (kPa)	Evaluates whether the foundation bearing capacity meets the load requirements of heavy facilities.	Benefit

Table 1. *Cont.*

Primary Criterion (Level 1)	Secondary Criterion (Level 2)	Code	Indicator (Level 3)	Description	Type
Socio-economic Benefits (B3)	Economic Benefits	C51	Potential Hinterland Cargo Volume (10^4 tons)	The estimated scale of waterborne cargo that the port can attract from its key economic hinterland.	Benefit
		C52	Long-term Development Potential	Evaluates whether sufficient shoreline and land space are reserved for future expansion.	Benefit
	Social Impacts	C61	Impact on Adjacent Residential Areas (0/1)	Whether the site is adjacent to population clusters (villages, schools), assessing noise and dust impacts.	Cost
		C62	Occupation of Arable Land/Homesteads (0/1)	Evaluates whether construction requires occupying arable land (esp. basic farmland) or homesteads.	Cost
		C63	Difficulty of Cross-Regional Coordination	Evaluates policy coordination difficulties if the site is located on a provincial boundary river.	Benefit
Environmental Protection (B4)	Ecological Constraints	C71	Ecological Red Line Constraints (0/1)	Whether the site occupies or is adjacent to statutory ecological protection red lines.	Cost
		C72	Ecological Vulnerability and Vegetation Impact	Evaluates the ecological fragility of the site and the impact of construction on vegetation and soil conservation.	Benefit
		C73	Construction Conditions for Environmental Facilities	Evaluates if there is sufficient land space to build sewage and waste treatment facilities.	Benefit

Notes: ① Indicator Type: (Benefit) indicates a higher value is better; (Cost) indicates a lower value is better. ② Qualitative Indicators (0–5 Scale): Scored by experts where 5 represents the optimal condition (e.g., very simple, high potential, low impact) and 0 represents the worst condition. ③ Binary Variables (0/1): For Cost-type indicators (e.g., C15, C61, C62, C71), 1 = Yes (disadvantageous, e.g., occupying red lines), 0 = No (advantageous). This binary treatment is adopted to reflect regulatory rigidity (e.g., ecological red lines) and data availability constraints in the reservoir area.

4. Methodology

Port site selection is a quintessential Multi-Criteria Decision-Making (MCDM) problem. Its evaluation indicator system (Table 1) encompasses four dimensions: Natural Conditions, Engineering Technology, Socio-economic Benefits, and Environmental Protection. However, in practical decision-making, the influence of individual indicators on the overall merit of the final site alternatives is not uniform. For instance, in mountainous regions characterized by complex topography and geology, the relative importance between factors concerning engineering feasibility and operational safety (e.g., geological hazard risks, bank slope stability) and those concerning core port functions and efficiency (e.g., dam-bypass transshipment efficiency, hinterland cargo sources) requires scientific quantification.

Therefore, to scientifically and objectively reflect the differences in relative importance among different indicators within a complex decision environment, it is essential to assign weights to the evaluation indicator system. The purpose of weighting is to assign a specific coefficient to each indicator to quantify its contribution or influence within the overall assessment, thereby ensuring that the final evaluation results align more closely with decision-making preferences and practical requirements.

4.1. Selection of Research Methodology

Port site selection in mountainous regions is fundamentally a complex Multi-Criteria Decision-Making (MCDM) problem. It involves multiple attributes—ranging from natural conditions and engineering technology to socio-economic factors—and aims to optimize comprehensive benefits. To comprehensively address the site selection challenges within the unique environment of the continuous dam area in the lower Jinsha River, and to effectively handle the disparities in indicator importance as well as the necessity for comparing multiple alternatives, this study constructs a comprehensive evaluation model incorporating combination weighting and multi-criteria ranking.

Crucially, the selection of specific methods within this model is driven by a decision logic tailored to the continuous dam zone. First, Linear Game Theory is selected to integrate weights. Unlike complex non-linear models, the linear approach offers higher stability and interpretability, ensuring a balanced trade-off between subjective expert caution (safety) and objective data efficiency (cost). While network-based approaches like ANP can explicitly model indicator interdependencies, this study maintains the AHP framework to preserve hierarchical clarity for engineering applications, utilizing Game Theory to objectively correct potential subjective correlation biases. Second, the EDAS method is employed for ranking. Given that mountainous geographic data often contains extreme values (outliers), EDAS (based on distance from average solutions) provides superior robustness regarding outliers compared to ideal-solution-based methods like TOPSIS. Theoretically, this is because "Ideal Solutions" are defined by extreme boundaries (Max/Min), which can be distorted by outliers, whereas the "Average Solution" used in EDAS serves as a stable "central gravity" point. Although EDAS implies a limitation regarding potential rank reversal when alternatives are added or removed, its stability in processing outlier data is prioritized for this fixed-set engineering evaluation. The specific research flowchart is illustrated in Figure 1.

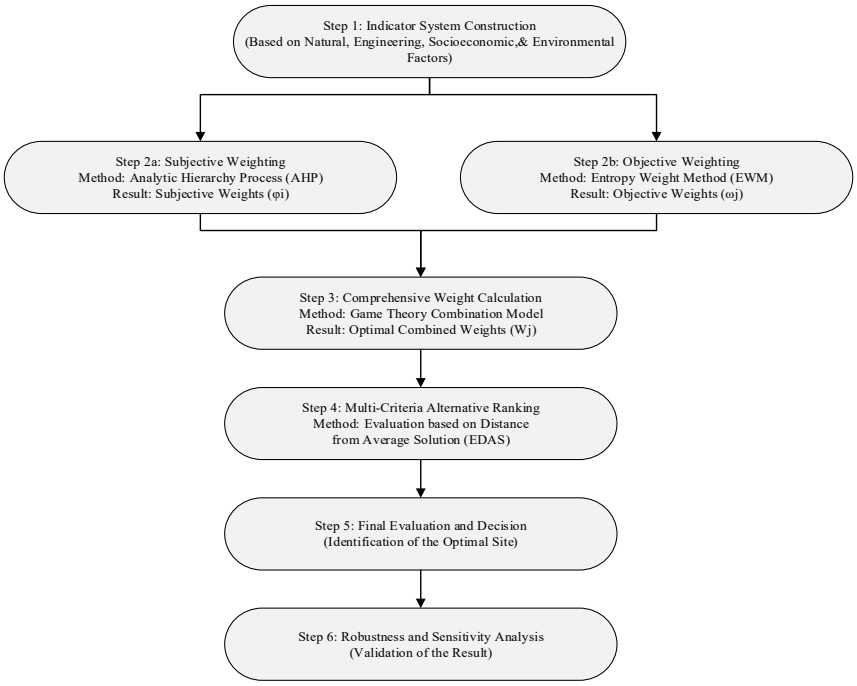


Figure 1. Research Methodology Flowchart. The arrows indicate the logical sequence of the research methodology steps.

Indicator Weighting Method Regarding indicator weighting, this study adopts a strategy that combines the Analytic Hierarchy Process (AHP) and the Entropy Weight Method (EWM). As a mature subjective weighting method, AHP can transform experts' qualitative judgments into quantitative weight coefficients by constructing pairwise comparison matrices, a technique successfully applied in port site selection research [30,31]. Conversely, EWM is an objective weighting method that determines weights based on the dispersion of the data itself [32]. However, both AHP and EWM have inherent limitations in practical application. Combining the two yields comprehensive weights that reflect both expert experience and the objective distribution characteristics of the data [33]. To integrate these methods effectively, this paper introduces a Game Theory model. This model calculates the final combined weights by identifying optimal combination coefficients that minimize

the deviation between the subjective and objective weights. This combined weighting approach has been widely applied in fields such as project investment decision-making, engineering evaluation, and risk assessment, proving effective in enhancing the reliability and logic of evaluation results [34].

For ranking the alternative sites, this paper selects the Evaluation based on the Distance from Average Solution (EDAS) model. Proposed by Keshavarz Ghorabaee et al. [35] in 2015, EDAS is a novel and robust Multi-Criteria Decision-Making (MCDM) method. Unlike other traditional methods (such as TOPSIS), the core advantage of the EDAS model lies in its use of the "Average Solution" rather than the "Ideal Solution" as the evaluation benchmark. In the context of mountainous port site selection, certain indicators (e.g., frequency of geological hazards, dam-bypass mileage) may exhibit extreme values due to specific topographic constraints. Traditional methods are susceptible to these outliers, which can cause the ideal solution to deviate from reality, thereby compromising evaluation accuracy. In contrast, EDAS evaluates performance by quantifying the "Positive Distance from Average" (PDA) and "Negative Distance from Average" (NDA). This mechanism effectively mitigates the impact of extreme outliers, offering higher mathematical robustness. Furthermore, the EDAS model has been successfully applied in diverse fields, including natural disaster assessment, logistics centre location selection, supplier selection, and the identification of barriers to renewable energy promotion [36–40].

4.2. Combination Weighting Based on Game Theory

4.2.1. Determination of Subjective Weights Using Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a method that decomposes complex decision-making problems into ordered hierarchical structures and determines the relative importance of elements at each level through a combination of qualitative and quantitative analysis. It effectively quantifies experts' subjective judgments. The calculation steps are as follows:

(1) Construct Judgment Matrices: Experts from relevant fields are invited to perform pairwise comparisons of indicators within the same criterion level using Saaty's 1–9 scale (Table 2) to construct the judgment matrix $\boldsymbol{A}$.

$$A = \left[a_{ij}\right]_{n\times m} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & \ddots & & a_{2m} \\ \vdots & & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix} \quad (1)$$

where $\boldsymbol{A}$ is the judgment matrix, and a_{ij} represents the relative importance of indicator i with respect to indicator j.

Table 2. Evaluation Scale and Meaning.

Scales	Interpretations
1	Factor i and j are equally important
3	Factor i is slightly more important than j
5	Factor i is significantly more important than j
7	Factor i is strongly more important than j
9	Factor i is extremely more important than j
2, 4, 6, 8	Intermediate values of the above scales
Reciprocal	If element i compared to j is a_{ij}, then j compared to i is $1/a_{ij}$

(2) Calculate Weight Vectors: Upon obtaining the judgment matrix, this paper employs the Geometric Mean Method (also known as the Square Root Method) to calculate the weight vector. First, calculate the geometric mean m_i of the elements in each row of the judgment matrix $\boldsymbol{A}$. Then, normalize the vector $\boldsymbol{M} = [m_1, m_2, \ldots, m_n]^{\mathrm{T}}$ to obtain the weight vector $\boldsymbol{\varphi} = [\varphi_1, \varphi_2, \ldots, \varphi_n]^T$. The calculation formulas are as follows:

$$m_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} (i = 1, 2, \ldots, n) \tag{2}$$

$$\varphi_i = \frac{m_i}{\sum_{i=1}^{n} m_i} \tag{3}$$

(3) Consistency Check: To ensure the reliability of the judgment results, the Consistency Ratio (CR) must be calculated for each matrix. The first step involves determining the maximum eigenvalue $\lambda_{\max}$. This is calculated by multiplying the judgment matrix $\boldsymbol{A}$ by the weight vector $\boldsymbol{\varphi}$, and then applying the following formula:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(\mathbf{A}\varphi)_i}{\varphi_i} \tag{4}$$

(4) Calculation of Consistency Ratio: The final parameter required is the Random Consistency Index (RI). Saaty determined RI values for pairwise comparisons involving up to 15 criteria, as shown in Table 3.

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

Table 3. Random Consistency Index (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

When $CR < 0.1$, the inconsistency of the judgment matrix is considered acceptable. Conversely, when $CR > 0.1$, the inconsistency exceeds the acceptable range; in this case, decision-makers must revise their pairwise comparison judgments and reconstruct the judgment matrix, repeating the process until the consistency test is passed.

It is acknowledged that AHP assumes indicator independence. While network-based methods (e.g., ANP) model dependencies, this study employs Game Theory to correct subjective biases with objective data, thereby mitigating the limitations of pure AHP in a more concise engineering framework.

4.2.2. Determination of Objective Weights Using Entropy Weight Method (EWM)

The Entropy Weight Method (EWM) is an objective weighting technique grounded in information entropy theory. It determines weights by calculating the entropy value of each indicator, which reflects the degree of dispersion in the data. The underlying logic is that if a specific indicator exhibits significant variation (i.e., high dispersion) across different evaluation objects, it provides a greater amount of valid information. Consequently, such an indicator is deemed more important and should be assigned a larger weight within the comprehensive evaluation system. Conversely, if the variation in an indicator's values is

minimal, with its information entropy approaching the maximum value, this indicates a scarcity of useful information, resulting in a relatively smaller weight. The calculation steps are as follows:

(1) Data Standardization: First, to eliminate dimensional differences among indicators, the raw data are standardized based on their attributes (benefit-type or cost-type), yielding the standardized value $X_{ij}^{'}$.

For benefit-type (positive) indicators:

$$X_{ij}^{'} = \frac{x_{ij} - \min\{x_i\}}{\max\{x_i\} - \min\{x_i\}} \tag{7}$$

For cost-type (negative) indicators:

$$X_{ij}^{'} = \frac{\max\{x_i\} - x_{ij}}{\max\{x_i\} - \min\{x_i\}} \tag{8}$$

(2) Calculation of Information Entropy: Calculate the information entropy E_j for the j-th indicator using the following formula:

$$f_{ij} = \frac{X_{ij}^{'}}{\sum_{i=1}^{n} X_{ij}^{'}} \tag{9}$$

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} f_{ij} \ln f_{ij} \tag{10}$$

(3) Calculation of Objective Weights: Determine the objective weight ω_j for each indicator based on its information entropy. A smaller entropy value implies a larger information utility value (1-E_j) and, therefore, a higher weight:

$$\omega_j = \frac{1 - E_j}{\sum_{j=1}^{m} (1 - E_j)} \tag{11}$$

4.2.3. Calculation of Combined Weights

After obtaining the subjective weight vector $\boldsymbol{\varphi} = [\varphi_1, \varphi_2, \ldots \varphi_n]^T$ via the Analytic Hierarchy Process (AHP) and the objective weight vector $\boldsymbol{\omega} = [\omega_1, \omega_2, \ldots \omega_n]^T$ via the Entropy Weight Method (EWM), it is necessary to determine their respective proportions in the final combined weights. This paper introduces Game Theory to couple the subjective and objective weights [41]. The fundamental premise is to determine an optimal combined weight vector $\boldsymbol{W}$ that minimizes the deviation between $\boldsymbol{W}$ and the two original weight vectors (ω and φ), thereby achieving a 'Nash Equilibrium' between subjective and objective assessments [42].

Any linear combination weight vector $\boldsymbol{W}$ can be expressed as

$$W = \alpha_1 \varphi + \alpha_2 \omega \tag{12}$$

where α_1 and α_2 are the linear combination coefficients.

According to Game Theory, to achieve the optimal solution, it is necessary to find a set of optimal allocation coefficients (α_1, α_2) that minimizes the deviation of the combined weight vector **W** from the two original vectors $\boldsymbol{\omega}$ and $\boldsymbol{\varphi}$. The expression for this optimization objective is as follows:

$$\min \left| \left| \mathbf{W} - \varphi \right| \right|_2^2 + \left| \left| \mathbf{W} - \omega \right| \right|_2^2 \tag{13}$$

According to the principles of matrix differentiation, by finding the first-order derivative of the above formula and setting it equal to 0, its optimal solution can be transformed into solving the following linear system of equations:

$$\begin{bmatrix} \varphi^T\varphi & \varphi^T\omega \\ \omega^T\varphi & \omega^T\omega \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} \varphi^T\varphi \\ \omega^T\omega \end{bmatrix} \tag{14}$$

By solving the above system of equations, the optimal allocation coefficients α_1 and α_2 are obtained. These are then normalized to derive the optimal combination coefficients β_1 and β_2:

$$\beta_1 = \frac{\alpha_1}{\alpha_1 + \alpha_2} \tag{15}$$

$$\beta_2 = \frac{\alpha_2}{\alpha_1 + \alpha_2} \tag{16}$$

Finally, the Game Theory-based combined weight W_j for the j-th indicator is calculated using the following formula:

$$W_{\mathrm{j}} = \beta_1\varphi_{\mathrm{j}} + \beta_2\omega_{\mathrm{j}} \tag{17}$$

It is important to address the inherent epistemic uncertainty and potential disagreement in expert assessments. While this study utilizes crisp values rather than fuzzy sets, the 'Uncertainty' is managed structurally through this Game Theory integration. By introducing the Entropy Weight Method (which relies solely on objective data variance), the model creates a correction mechanism. If expert judgments contain high cognitive bias or uncertainty that contradicts the data reality, the optimization process of Game Theory automatically adjusts the final weights to a Nash Equilibrium, thereby mitigating the risk of relying exclusively on subjective uncertainty.

4.3. Ranking of Alternatives Based on the EDAS Method

To rank the alternative port sites, this study employs the EDAS model. This method evaluates the comprehensive performance of alternatives by quantifying the degree of their deviation from the average solution. The specific calculation steps are outlined below:

Step 1: Construct the Initial Decision Matrix

Assume there are m alternatives and n evaluation indicators. The initial decision matrix $\boldsymbol{X}$ is constructed as follows:

$$X = \left[x_{ij}\right]_{m\times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & \ddots & & x_{2n} \\ \vdots & & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{18}$$

where x_{ij} represents the value of the i-th alternative with respect to the j-th indicator.

Step 2: Calculate the Average Solution (AV)

Calculate the arithmetic mean of all alternatives for each indicator j to obtain the average solution vector AV:

$$AV = \left[AV_j\right]_{1\times n} \tag{19}$$

$$AV_j = \frac{\sum_{i=1}^{m} x_{ij}}{m} \tag{20}$$

Step 3: Calculate Positive Distance from Average (PDA) and Negative Distance from Average (NDA)

Calculate the PDA and NDA for each alternative's score x_{ij} relative to the average solution AV_j based on the indicator type (Benefit-type or Cost-type).

For Benefit-type indicators:

$$PDA_{ij} = \frac{\max(0, (X_{ij} - AV_j))}{AV_j} \tag{21}$$

$$NDA_{ij} = \frac{\max(0, (AV_j - X_{ij}))}{AV_j} \tag{22}$$

For Cost-type indicators:

$$PDA_{ij} = \frac{\max(0, (AV_j - X_{ij}))}{AV_j} \tag{23}$$

$$NDA_{ij} = \frac{\max(0, (X_{ij} - AV_j))}{AV_j} \tag{24}$$

Here, PDA_{ij} represents the component of alternative i that is "superior to the average" on indicator j, while NDA_{ij} represents the component that is "inferior to the average."

Step 4: Calculate Weighted Sum of PDA (SP_i) and NDA (SN_i)

Incorporating the combined weights (W_j) derived in Section 4.2.3, calculate the weighted sum of PDA and NDA for each alternative i to obtain the Weighted Sum of Positive Distances (SP_i) and Weighted Sum of Negative Distances (SN_i):

$$SP_i = \sum_{j=1}^{n} W_j \cdot PDA_{ij} \tag{25}$$

$$SN_i = \sum_{j=1}^{n} W_j \cdot NDA_{ij} \tag{26}$$

Step 5: Normalize SP_i and SN_i Values

To eliminate dimensional differences, normalize the SP_i and SN_i values for all alternatives:

$$NSP_i = \frac{SP_i}{\max_i(SP_i)} \tag{27}$$

$$NSN_i = 1 - \frac{SN_i}{\max_i(SN_i)} \tag{28}$$

Step 6: Calculate the Appraisal Score (AS_i)

Calculate the final Appraisal Score (AS_i) for each alternative i. This score integrates the performance of being superior to the average (NSP_i) and inferior to the average (NSN_i):

$$AS_i = \frac{1}{2}(NSP_i + NSN_i) \tag{29}$$

where $0 \leq AS_i \leq 1$. The alternatives are ranked in descending order of their AS_i values. A higher AS_i indicates better comprehensive performance of the alternative.

5. Case Validation

5.1. Case Overview

The Xiluodu Hydropower Station is a backbone project in the "four-level cascade" development of the lower Jinsha River, situated in a V-shaped canyon at the border of Leibo County, Sichuan Province, and Yongshan County, Yunnan Province. Its construction has fundamentally altered local hydrological and navigation conditions, providing a typical, realistic context for this study.

(1) Fundamental Changes and Challenges in Navigation Conditions: The Xiluodu Dam stands 285.5 m high, forming a massive reservoir with a total capacity of 12.67 billion cubic meters. Impoundment created a 194 km deep-water reservoir channel. The 167 km perennial backwater zone offers superior navigation conditions, meeting standards for 3000-ton fleets [43]. However, the dam physically interrupts navigation continuity. Therefore, constructing an efficient dam-bypass terminal to link the upstream reservoir with the downstream shipping lane is the key to restoring full-line connectivity.

(2) Unique Natural Environmental Constraints on Site Selection: The valley at the dam site presents an asymmetric "V" shape with steep terrain on both banks. The right bank (Yunnan side) is particularly precipitous, while the left bank (Sichuan side) is relatively gentler but possesses limited flat land space suitable for port construction. Meanwhile, influenced by the deeply incised high mountain canyon terrain, geological hazard bodies such as landslides and collapses are frequent on both banks of the reservoir area. These complex engineering geological conditions pose potential threats to port structures and operational safety.

(3) Regional Economic Hinterland and Cargo Source Basis: The economic feasibility of terminal site selection depends on cargo support from its hinterland. The socio-economic development on both banks of the Xiluodu Reservoir area has distinct characteristics, constituting the primary service targets for the future port. On the left bank, Leibo County in Sichuan Province is rich in mineral resources; 13 mineral types have been proven, with huge phosphate reserves making it one of China's eight major high-quality phosphate mining areas and a potential source of bulk cargo [44]. On the left bank, Leibo County in Sichuan Province possesses abundant mineral resources, particularly massive phosphate reserves [44], providing a stable source of bulk cargo. On the right bank, Yongshan County relies on the unique climate of the dry-hot valley to develop a competitive agricultural sector featuring characteristic cash crops [45,46]. These distinct industrial structures generate sustained demand for the outbound transport of mineral products and agricultural produce, alongside the inbound transport of production materials.

(4) Conformity with Macro-Planning and Strategic Opportunities: According to the *Sichuan Province Inland Water Transport Development Plan* and the joint strategic deployment by Sichuan and Chongqing, constructing a dam-bypass transport system for the lower Jinsha River cascades (including Xiluodu) is an established goal to restore full-line navigation [47]. Consequently, this site selection aligns directly with these national and regional logistics strategies, ensuring necessary policy support for project implementation.

5.2. Alternatives and Data Acquisition

Based on preliminary planning and field reconnaissance, and referencing relevant engineering technical data, three relatively favorable alternative port sites were identified upstream of the Xiluodu Dam: Jinshakou and Huangjuebao on the left bank (Sichuan Province), and Majiaheba on the right bank (Yunnan Province), as shown in Figure 2.

Option A (Jinshakou): Located in Leibo County, Liangshan Prefecture, Sichuan Province, on the left bank of the Jinsha River, this site is approximately 7.5 km from the Xiluodu dam site. The site boasts a utilizable shoreline length of about 930 m, which constitutes its primary advantage. However, its disadvantages are equally pronounced: the bank slope is precipitous, and the available land space is extremely narrow. Consequently, large-scale construction would entail significant engineering difficulties and high investment costs, coupled with relatively poor geological stability. Currently, a simple terminal has already been constructed at Jinshakou.

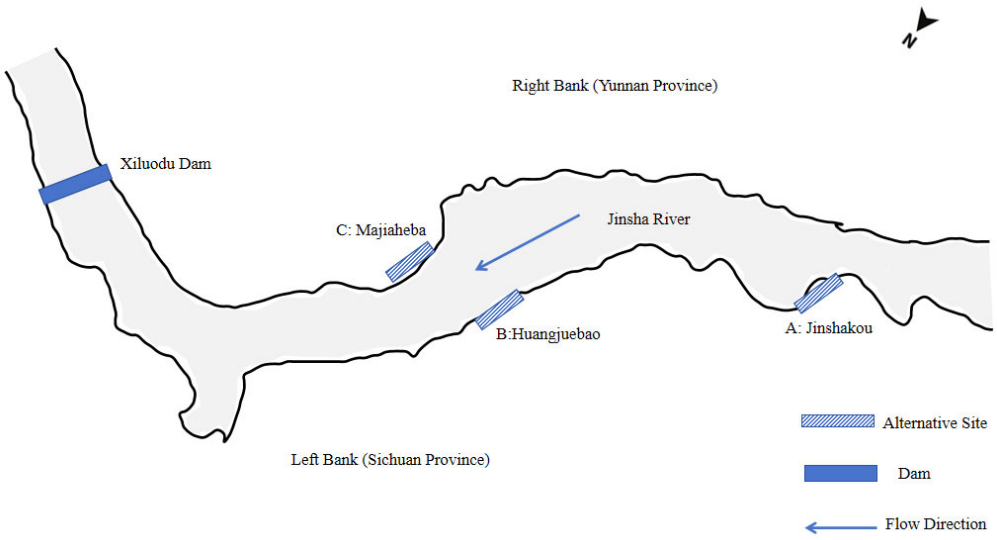


Figure 2. Schematic Diagram of Alternative Port Site Locations Upstream of Xiluodu.

Option B (Huangjuebao): Also situated in Leibo County, Liangshan Prefecture, Sichuan Province, on the left bank of the Jinsha River, this site is located 3.7 km upstream of the Xiluodu dam site, downstream of Jinshakou. The bank slope conditions here are slightly superior to those at Jinshakou, offering some developable land space. The overall conditions of this site are relatively intermediate; its bank slope and land space are better than Jinshakou's but inferior to Majiaheba's. However, it still faces limitations regarding insufficient land space to support large-scale port construction. Furthermore, compared to the Majiaheba site, it is farther from the Xiluodu Dam, resulting in reduced economic efficiency. Additionally, with residential areas and schools located near the rear, the construction and operation of the terminal could potentially disturb the surrounding community.

Option C (Majiaheba): Located on the right bank (within Yongshan County, Zhaotong City, Yunnan Province), approximately 3.5 km upstream of the dam, this is the closest site to the dam among the three alternatives. Its main advantage lies in having the shortest dam-bypass distance, theoretically offering the highest transshipment efficiency. The site features a relatively gentle natural bank slope with a frontage gradient of approximately 1:3. Although backed by steep slopes, it possesses the most extensive riverside terrace among the three options, with a utilizable shoreline of about 600 m and a land depth of approximately 200 m. A maritime patrol vessel terminal for the Three Gorges Corporation has already been built downstream. Its primary challenge is the high, steep slope at the rear, which necessitates the construction of new tunnels for external transport connections.

To provide a more intuitive comparison of the core differences among the alternatives, their key characteristics are summarized in Table 4.

Table 4. Comparison of Key Characteristics of the Three Alternative Port Sites.

Comparison Dimension	Option A (Jinshakou)	Option B (Huangjuebao)	Option C (Majiaheba)
Bank Location	Left Bank (Sichuan side)	Left Bank (Sichuan side)	Right Bank (Yunnan side)
Distance to Dam	km Approx. 7.5 km	Approx. 3.7 km	Approx. 3.5 km
Topography and Landform	Precipitous bank slope	Moderate bank slope	Riverside terrace, gentle bank slope
Land Space	Extremely narrow	Insufficient	Relatively open
Adjacent Residential Areas	No	Yes (Residential areas and schools)	No
External Connectivity	Upgrade existing roads	Upgrade existing roads	New tunnel construction is required
Primary Hinterland	Cargo from the Sichuan side	Cargo from the Sichuan side	Cargo from the Yunnan side

The evaluation data for this paper were primarily obtained through two channels: expert questionnaires and document review. On one hand, to determine the subjective weights via AHP, eight experts from relevant fields were invited to conduct pairwise comparisons of the indicators at each level within the indicator system to judge their relative importance. The panel was carefully structured to balance theoretical rigor, engineering feasibility, and policy compliance, comprising two academic scholars, three senior engineers, and three government officials. The detailed profiles of the experts are presented in Table 5. On the other hand, to construct the initial decision matrix for the subsequent evaluation model (EDAS), the data sources were categorized into two parts:

(1) Qualitative Indicator Data: (e.g., C41 Difficulty of Berth Hydraulic Structure Construction, C52 Long-term Development Potential, C63 Difficulty of Cross-Regional Coordination). These indicators were scored by experts based on detailed data regarding the three alternative sites (including but not limited to engineering geological conditions, hydrological characteristics, and satellite imagery) according to a pre-defined 0–5 scoring scale, and the arithmetic mean was calculated.

(2) Quantitative Indicator Data: (e.g., C31 Road Transshipment Distance for Dam Bypass, C12 Water Depth at Terminal Frontage, C22 Frequency of Geological Hazards, and C51 Potential Hinterland Cargo Volume). These data were primarily obtained by consulting relevant engineering technical documents, conducting map measurement estimations, and analyzing industry reports and regional plans.

Table 5. Profiles of the Expert Panel.

Expert ID	Affiliation Type	Professional Title	Specialization/Expertise	Working Experience (Years)
E1	University	Professor	Port and Coastal Engineering	22
E2	University	Professor	Waterway Transportation Planning	18
E3	Design Institute	Senior Engineer	Port Hydraulic Structure Design	20
E4	Design Institute	Senior Engineer	Geotechnical Engineering	16
E5	Design Institute	Senior Engineer	River Navigation Channel Engineering	15
E6	Government	Official	Regional Strategy and Logistics	16
E7	Government	Official	Port and Shipping Administration	18
E8	Government	Official	Transport Planning and Investment	17

5.3. Results and Analysis

(1) Initial Decision Matrix

Based on the data acquisition methods described in Section 5.2, the objective data for quantitative indicators and the arithmetic means of expert ratings for qualitative indicators were aggregated. This formed the initial decision matrix containing three alternatives (Options A, B, and C) and 23 specific indicators (Table 6). This matrix serves as the foundation for the subsequent calculations using the Entropy Weight Method (EWM) and the EDAS model.

Table 6. Evaluation Results for Alternative Port Sites.

Level 3 Indicator	Type	Option A	Option B	Option C
Channel Flow Velocity(m/s)	Cost	1.1	1	1
Water Depth at Terminal Frontage	Benefit	4.8	5.1	5.3
Channel Width	Benefit	160	280	300
Water Level Fluctuation Amplitude	Cost	2.8	3	3
Impact of Fluctuating Backwater Zone	Cost	1	1	1
Seismic Fortification Intensity	Cost	8	8	8
Frequency of Geological Hazards	Cost	0.2	0.3	0.1
Bank Slope Angle (Stability)	Cost	1	0.3	0.33
Available Land Width (Depth)	Benefit	100	140	200

Table 6. *Cont.*

Level 3 Indicator	Type	Option A	Option B	Option C
Usable Shoreline Length	Benefit	930	460	600
Road Transshipment Distance for Dam Bypass	Cost	21.6	19.3	18.5
Construction Length of Connecting Access Roads	Cost	2	3.7	1.5
Difficulty of Berth Hydraulic Structure Construction	Benefit	3.15	4.25	4.1
Conditions for Accessing Supporting Facilities	Benefit	3.78	4.5	3.9
Land Bearing Capacity	Benefit	2000	1500	2000
Potential Hinterland Cargo Volume	Benefit	710	710	600
Long-term Development Potential	Benefit	3.9	3.6	4.25
Impact on Adjacent Residential Areas	Cost	0	1	0
Occupation of Arable Land/Homesteads	Cost	0	1	0
Difficulty of Cross-Regional Coordination	Benefit	3.55	3.7	4.6
Ecological Red Line Constraints	Cost	0	0	0
Ecological Vulnerability and Vegetation Impact	Benefit	4.16	3.67	3.9
Construction Conditions for Environmental Facilities	Benefit	3	3.6	4.12

(2) Weight Calculation

Determination of Subjective Weights using AHP: Based on the pairwise comparisons of indicator importance by experts, the subjective weights (φ_i) for each indicator were calculated using the AHP method. All judgment matrices passed the consistency test (CR < 0.1), and the results are presented in Table 7.

Table 7. Calculation Results of Subjective Weights via AHP.

Primary Criterion	Weight (W_B)	Secondary Criterion	Weight (Wc)	Indicator	Subjective Weight (φ_i)
Natural Conditions (B1)	0.3924	Water Conditions(C1)	0.4001	C11	0.0214
				C12	0.0466
				C13	0.0505
				C14	0.0214
				C15	0.0171
		Land Conditions(C2)	0.5999	C21	0.0242
				C22	0.0818
				C23	0.0489
				C24	0.0438
				C25	0.0368
Engineering Technology (B2)	0.2937	Collection and Distribution(C3)	0.5756	C31	0.1016
				C32	0.0675
		Port Construction(C4)	0.4244	C41	0.0422
				C42	0.0149
				C43	0.0675
Socio-economic Benefits (B3)	0.1914	Economic Benefits(C5)	0.6631	C51	0.0762
				C52	0.0507
		Social Impacts(C6)	0.3369	C61	0.0291
				C62	0.0218
				C63	0.0135
Environmental Protection (B4)	0.1225	Ecological Constraints(C7)	1.0000	C71	0.0497
				C72	0.0359
				C73	0.0370

Note: For the detailed definitions of the indicators (C11–C73), please refer to Table 1.

Determination of Objective Weights using EWM: Using the initial decision matrix (Table 6) as the raw data matrix, the information entropy (E_j) and objective weights (ω_j) for

each evaluation indicator were calculated using the Entropy Weight Method. The results are shown in Table 8.

Table 8. Calculation Results of Objective Weights via EWM.

Indicator	Information Entropy (E_j)	Information Redundancy (d_j)	Objective Weight (ω_j)
C11	0.6309	0.3691	0.0408
C12	0.6022	0.3978	0.0439
C13	0.6282	0.3718	0.0411
C14	0.0000	1.0000	0.1104
C15	1.0000	0.0000	0.0000
C21	1.0000	0.0000	0.0000
C22	0.5794	0.4206	0.0465
C23	0.6307	0.3693	0.0408
C24	0.5446	0.4554	0.0503
C25	0.4903	0.5097	0.0563
C31	0.6209	0.3791	0.0419
C32	0.6234	0.3766	0.0416
C41	0.6285	0.3715	0.0410
C42	0.3733	0.6267	0.0692
C43	0.6309	0.3691	0.0408
C51	0.6309	0.3691	0.0408
C52	0.5677	0.4323	0.0477
C61	0.6309	0.3691	0.0408
C62	0.6309	0.3691	0.0408
C63	0.3430	0.6570	0.0726
C71	1.0000	0.0000	0.0000
C72	0.5702	0.4298	0.0475
C73	0.5887	0.4113	0.0454

Determination of Combined Weights: The Game Theory model was introduced to combine the subjective and objective weights, yielding the final comprehensive weights (W_j), where the optimal combination coefficients were calculated as $\beta_1 = 0.4978$ and $\beta_2 = 0.5022$ (Table 9).

Table 9. Combination Weighting Results Based on Game Theory.

Indicator	Type	Subjective Weight (φ_i)	ObjectiveWeight (ω_j)	Game Theory Combined Weight (W_j)
C11	Cost	0.0214	0.0408	0.0311
C12	Benefit	0.0466	0.0439	0.0452
C13	Benefit	0.0505	0.0411	0.0458
C14	Cost	0.0214	0.1104	0.0661
C15	Cost	0.0171	0.0000	0.0085
C21	Cost	0.0242	0.0000	0.0120
C22	Cost	0.0818	0.0465	0.0641
C23	Cost	0.0489	0.0408	0.0448
C24	Benefit	0.0438	0.0503	0.0471
C25	Benefit	0.0368	0.0563	0.0466
C31	Cost	0.1016	0.0419	0.0716
C32	Cost	0.0675	0.0416	0.0545
C41	Benefit	0.0422	0.041	0.0416
C42	Benefit	0.0149	0.0692	0.0422
C43	Benefit	0.0675	0.0408	0.0541
C51	Benefit	0.0762	0.0408	0.0584
C52	Benefit	0.0507	0.0477	0.0492
C61	Cost	0.0291	0.0408	0.0350
C62	Cost	0.0218	0.0408	0.0313
C63	Benefit	0.0135	0.0726	0.0432
C71	Cost	0.0497	0.0000	0.0247
C72	Benefit	0.0359	0.0475	0.0417
C73	Benefit	0.0370	0.0454	0.0412

(3) Ranking of Alternatives Based on the EDAS Method

Based on the initial decision matrix (Table 6) derived earlier and the calculated combined indicator weights (Table 9), the EDAS method was applied to evaluate and rank the alternatives. The results are presented in Table 10.

Table 10. EDAS Evaluation Results for Alternative Port Sites.

Alternative	SP_i	SN_i	NSP_i	NSN_i	AS_i	Rank
Option A (Jinshakou)	0.1079	0.1011	0.5488	0.5625	0.5557	2
Option B (Huangjuebao)	0.0419	0.2312	0.2134	0.0000	0.1067	3
Option C (Majiaheba)	0.1966	0.0141	1.0000	0.9391	0.9695	1

The results indicate that Option C (Majiaheba) has the highest AS_i value (0.9695), identifying it as the optimal alternative; Option A (Jinshakou) follows in second place, while Option B (Huangjuebao) ranks last.

5.4. Discussion

The results of this empirical analysis indicate that Option C (Majiaheba site) is the optimal choice among the three alternatives; Option A (Jinshakou) follows, and Option B (Huangjuebao) ranks last.

Specifically, Option C (Majiaheba) exhibits prominent comprehensive performance and represents the most balanced solution among the alternatives. Majiaheba possesses the most extensive and gentle riverside terrace among the three options, and the relatively gentle natural bank slope provides a solid geological foundation for terminal construction. Moreover, its weighted sum of positive distances (SP_i = 0.1966) is the highest, while its weighted sum of negative distances (SN_i = 0.0141) is the lowest. Its core advantages align well with the indicators assigned the highest weights by the Game Theory combination weighting in this study. Among the three indicators with the highest weights, Option C performs optimally in both C31 (Road Transshipment Distance for Dam Bypass) and C22 (Frequency of Geological Hazards). Although it does not perform as well as Option A in C14 (Water Level Fluctuation Amplitude)—which holds the second-highest weight—its distinct advantages in several key indicators, such as C32 (Construction Length of Connecting Access Roads), C24 (Available Land Width), and C63 (Difficulty of Cross-Regional Coordination), largely offset its hydrological disadvantages. This allows it to achieve a significantly higher comprehensive score than the other alternatives. Specifically, Option C effectively balances the trade-offs between transport efficiency and environmental impact, avoiding the occupation of ecological red lines while minimizing geological risks.

Option A (Jinshakou) (AS_i = 0.5557) ranks second. Its primary advantages lie in possessing the longest utilizable shoreline length and the optimal score in C72 (Ecological Vulnerability). However, its main constraining factors are engineering feasibility and hydrological conditions. It performs poorly in C23 (Bank Slope Angle) and C24 (Available Land Width), reflecting the precipitous bank slope and narrow available land space at this location. Crucially, such high exposure to complex geological structures constitutes a significant engineering safety hazard, potentially compromising the port's all-weather operational reliability. This implies high engineering difficulty and investment for large-scale construction. Despite its deficiencies in engineering conditions, it avoids the significant disadvantages in social impact seen in Option B. Therefore, the model identifies it as the sub-optimal alternative.

In contrast, the appraisal value of Option B (Huangjuebao) (AS_i = 0.1067) is significantly lower than the other two alternatives13. The main deficiency of Option B lies in its social impact indicators. It is the only option with disadvantages in both C61 (Impact on Adjacent Residential Areas) and C62 (Occupation of Arable Land/Homesteads). This

foreshadows potential disturbances to resident life and complex land acquisition issues during project implementation. From a long-term perspective, such factors may lead to complex social conflicts, which might pose challenges to stakeholder coordination and affect the project's long-term stability. Meanwhile, its performance in C32 (Construction Length of Connecting Access Roads) is relatively unfavorable among the three options, leading to poor collection and distribution conditions.

Additionally, the Majiaheba site has been explicitly included in relevant national, provincial, and municipal plans. It is highly consistent with the functional positioning reserved for Majiaheba in the *Zhaotong City Port Terminal Shoreline Plan*—a "core hub for dam-bypass transshipment of bulk cargo" [48]. This top-down planning conformity provides a crucial guarantee for the smooth implementation of the project.

The distribution of the final combined weights in this evaluation is the result of the interplay (game) between the subjective expert preferences derived from AHP and the objective data characteristics captured by EWM. This distribution exhibits a distinct hierarchical structure, reflecting the intrinsic decision-making logic for port site selection within the unique environment of the high mountain gorges of the lower Jinsha River.

Regarding the weight distribution of the primary criteria (as shown in Figure 3), Natural Conditions accounts for the highest proportion at 41.13%; followed by Engineering Technology at 26.39%; then Socio-economic Benefits (B3) at 21.71%; and finally Environmental Protection at 10.77%. This distribution clearly demonstrates that in the complex decision-making process for mountainous port site selection, "Natural Conditions"—comprising geology, bank slopes, and hydrology—constitute the fundamental factors prioritized by the model.

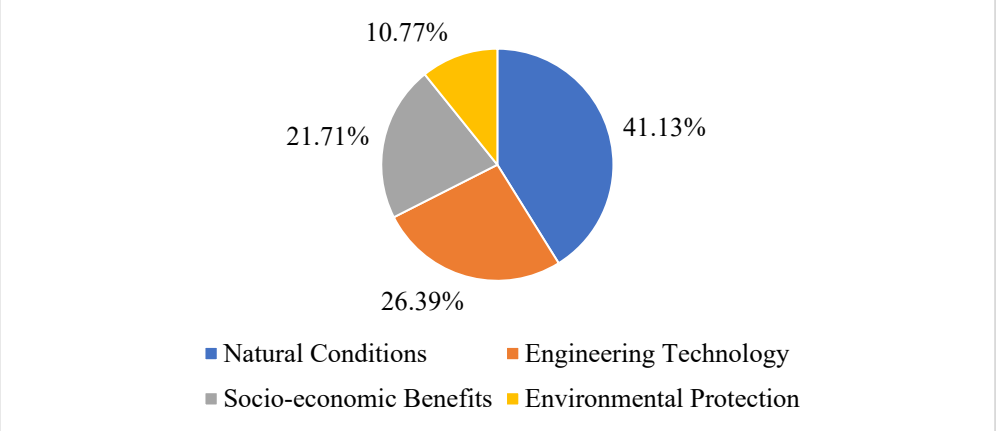


Figure 3. Weight Distribution of the First-Level Criteria.

Regarding the final weight ranking of all 23 specific indicators (as shown in Figure 4), the indicators with the highest weights are C31 (Road Transshipment Distance for Dam Bypass), C14 (Water Level Fluctuation Amplitude), and C22 (Frequency of Geological Hazards). This result distinctly reflects the characteristics of combining subjective and objective weighting:

(1) The high weight of C31 (Road Transshipment Distance for Dam Bypass) is primarily inherited from the AHP method (where it had a subjective weight of 0.1016, ranking 1st). This reflects the experts' consensus that "dam-bypass efficiency" constitutes the core function and a prerequisite for port site selection in mountainous dam-bypass areas.

(2) The reason C14 (Water Level Fluctuation Amplitude) ranks highly (despite a low AHP weight of 0.0214 and a poor ranking; it had an EWM weight of 0.1104, ranking 1st) is entirely due to the contribution of objective weighting. This indicates that within the raw

data, C14 is the indicator that distinguishes the pros and cons of the three alternatives with the greatest degree of differentiation.

(3) The high weight of C22 (Frequency of Geological Hazards) results from its prominent ranking in both subjective and objective weighting outcomes, indicating that "geological safety" is a critical factor both subjectively and objectively.

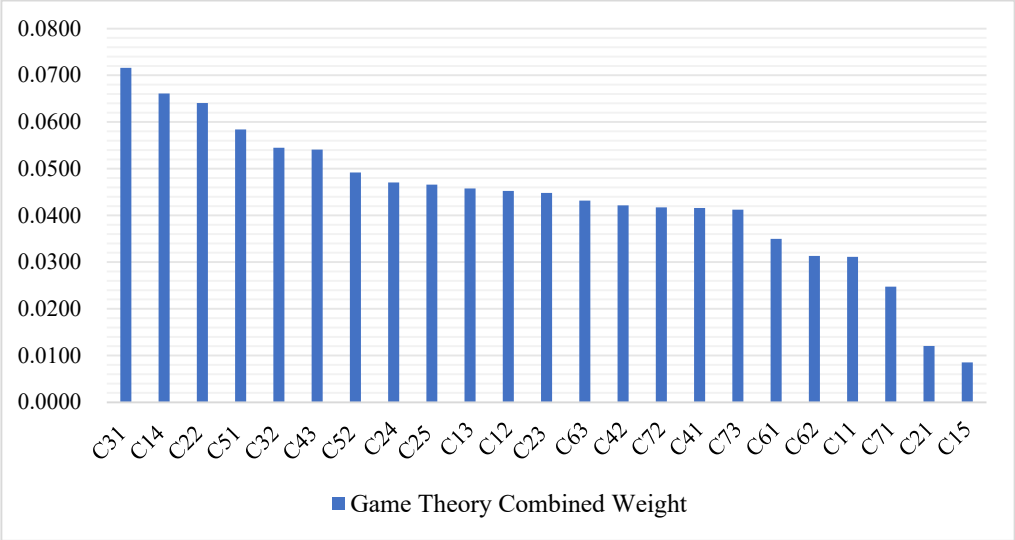


Figure 4. Final Composite Weights and Ranking of All Indicators.

In traditional mountainous river site selection, natural mountainous rivers often exhibit high flow velocities and steep gradients, accompanied by adverse flow regimes. Consequently, "hydrological conditions" per se (such as flow velocity and water depth) are usually decisive constraining factors [49]. However, in the weighting system of this study, the specific indicators categorized under the "Water Conditions" secondary criterion do not rank highly. In particular, the final weights of C11 (Channel Flow Velocity) and C15 (Impact of Fluctuating Backwater Zone) are both at the bottom. This does not imply that hydrological conditions are unimportant. Rather, it is because the construction of the Xiluodu Dam has transformed the former V-shaped canyon channel into a deep-water reservoir area with stable water levels and high navigation grades, forming a 194-km-long deep-water channel. This implies that for the three alternative port sites located close to each other within the upstream reservoir area, the macro-hydrological environment they face has become consistent, and all meet the requirements. Therefore, the focus of selection has shifted from water to land, with the physical feasibility and engineering safety of the alternative sites serving as important prerequisites.

5.5. Sensitivity and Comparative Analysis

To further examine the consistency and stability of the evaluation results, this section conducts a sensitivity analysis from two dimensions: decision-making models and decision preferences. First, four other Multi-Criteria Decision-Making (MCDM) models are introduced to cross-validate the ranking results of the EDAS model. Second, different weighting scenarios are established to test the sensitivity of the final ranking to changes in decision preferences.

5.5.1. Comparative Analysis with Other MCDM Methods

To verify the validity and consistency of the ranking results obtained by the EDAS model used in this study, four MCDM models widely applied in academic and engineering fields were introduced for cross-validation: TOPSIS, VIKOR, COPRAS, and ARAS. Keeping the initial decision matrix (Table 6) and the final combined weights (Table 9) from this

study constant, these five models (including EDAS) were used independently to rank the alternatives. The comparison of the ranking results is shown in Table 11.

Table 11. Comparison of Ranking Results between EDAS and Other MCDM Models.

Alternative	EDAS Rank	TOPSIS Rank	VIKOR Rank	ARAS Rank	COPRAS Rank
Option C	1	1	1	1	1
Option A	2	2	3	2	2
Option B	3	3	2	3	3

As seen in Table 11, although the evaluation logic of the five models differs, all five methods identified Option C as the optimal alternative. Among them, only the VIKOR method produced a different ranking order for the other options. This discrepancy is due to the unique algorithmic logic of the VIKOR model (a compromise between maximizing "group utility" and minimizing "individual regret"), which makes it less sensitive to the disadvantages of Option B (e.g., C61, C62) compared to EDAS or TOPSIS.

The comparative test results across different models indicate that the conclusion of this paper is consistent; specifically, the selection of the optimal alternative (Option C) does not depend on the choice of a specific evaluation method.

5.5.2. Sensitivity to Decision Preferences

To test the stability of the ranking results under different decision preferences, this study simulated three different weighting scenarios and compared them with a "Baseline Scenario." By adjusting the weight proportion of the primary criteria (increasing the weight of the target criteria by 20% and proportionally normalizing the others), different decision preferences were simulated:

(1) Baseline Scenario: Adopts the final combined weights derived in Section 5.4 (B1 = 41.1%, B2 = 26.4%, B3 = 21.7%, B4 = 10.8%).

(2) Scenario S1 (Safety Priority): Increases the weight proportion of B1 (Natural Conditions) by 20%, simulating a preference where decision-makers prioritize geological safety and physical feasibility.

(3) Scenario S2 (Efficiency and Economy Priority): Increases the weight proportions of B2 (Engineering Technology) and B3 (Socio-economic Benefits) by 20% each, simulating a preference where decision-makers focus more on dam-bypass efficiency and potential cargo sources.

(4) Scenario S3 (Environment and Social Priority): Increases the weight proportions of B3 (Socio-economic Benefits) and B4 (Environmental Protection) by 20% each, simulating a preference where decision-makers are more concerned with social impacts and ecological protection.

The EDAS model was re-run using these four different sets of combined weights. The final appraisal scores (AS_i) and rankings obtained are shown in Table 12.

Table 12. Sensitivity Analysis Results Under Different Scenarios.

Scenario	Option A	Option B	Option C	Rank_A	Rank_B	Rank_C
Baseline Scenario	0.5557	0.1067	0.9695	2	3	1
Scenario S1	0.4962	0.1158	0.9673	2	3	1
Scenario S2	0.6199	0.0977	0.9717	2	3	1
Scenario S3	0.6048	0.0962	0.9708	2	3	1

Analysis of Table 12 reveals that although the AS_i values varied across the three scenarios, the final ranking results remained unchanged. This confirms the robustness of

Option C (Majiaheba). Even under significant shifts in decision preferences, it consistently maintains its status as the optimal solution.

However, it should be noted that the validation in this study is based on the specific context of the Jinsha River. While the framework demonstrates strong adaptability to this high-constraint environment, its generalizability to other river basins with different geological or policy conditions requires further verification through broader case studies.

6. Conclusions

Set against the backdrop of the unique and complex environment of a mountainous continuous dam area, this paper systematically constructs an evaluation indicator system for dam-bypass port site selection across four dimensions: Natural Conditions, Engineering Technology, Socio-economic Benefits, and Environmental Protection. Subjective weights were determined via the Analytic Hierarchy Process (AHP), objective weights via the Entropy Weight Method (EWM), and optimal combined weights were derived through a Game Theory model. Finally, the EDAS model was applied to rank and optimize the alternatives. Through the empirical analysis of three alternative port sites in the Xiluodu Reservoir area, the following main conclusions are drawn:

(1) The application results clearly point to the optimal site selection alternative. The hybrid evaluation framework constructed in this study demonstrates high practical applicability. The calculation results (AS_i) from the EDAS model exhibit significant differentiation, yielding a final ranking of Option C (Majiaheba) > Option A (Jinshakou) > Option B (Huangjuebao). The model successfully quantifies the comprehensive advantages and disadvantages of each alternative, providing quantitative decision support for decision-making regarding the Xiluodu dam-bypass port site.

(2) The study reveals the core decision-making logic for dam-bypass port site selection within the specific environment of a mountainous dam area. The results of the Game Theory combination weighting indicate that the indicators with the highest weights are C31 (Road Transshipment Distance for Dam Bypass), C14 (Water Level Fluctuation Amplitude), and C22 (Frequency of Geological Hazards). This suggests that following the construction of large-scale hydropower complexes, the focus of upstream site selection has shifted from traditional hydrological conditions (e.g., flow velocity, water depth) to a comprehensive consideration of operational efficiency (C31), operational stability risk (C14), and engineering-geological safety (C22).

(3) The evaluation results demonstrate significant stability and internal consistency. First, in the comparative test of methods, four additional MCDM models were introduced for cross-validation, all of which confirmed Option C as the optimal alternative. Second, in the scenario analysis, three different decision preferences were simulated, and the optimal ranking remained unchanged. This indicates that the selection of Option C is insensitive to specific methodological variations, confirming it as a reliable engineering decision for the Xiluodu Reservoir area.

Based on the findings of this paper, the following recommendations and future outlooks are proposed:

(1) The evaluation system and methodology proposed herein not only provide a direct decision-making basis for the Xiluodu dam-bypass port site selection in the lower Jinsha River but also offer a reference for the planning of port groups in similar mountainous cascade hydropower hubs. Applying this framework contributes to the scientific planning of regional inland waterway transport by ensuring that infrastructure projects are effectively adapted to the complex local environment. Based on this, it is recommended that relevant planning departments adopt a "Two-Stage Screening Method" during the preliminary site selection for similar projects. Stage 1: Conduct preliminary screening using physical

feasibility (centered on geological and spatial conditions) as a rigid constraint. Stage 2: Apply the multi-objective comprehensive evaluation model constructed in this paper to the screened alternatives to achieve scientific decision-making.

(2) The evaluation data in this paper relied on expert questionnaires and the interpretation of existing engineering reports. While sufficient for this case study, the sample size suggests room for broader consultation in future iterations. Future research could employ the Delphi method to conduct multiple rounds of consultation with a broader group of experts to enhance data consensus. Additionally, future evaluation models could introduce dynamic analysis; for instance, combining System Dynamics to simulate the impact of dynamic changes in cargo volume on long-term operational benefits. Furthermore, future models should assess "dynamic adaptability," such as investigating in depth the specific impact of reservoir peak-shaving (e.g., C14 Water Level Fluctuation) on all-weather operational safety.

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Abbreviations

The following abbreviations are used in this manuscript:

ARAS	Additive Ratio Assessment
COPRAS	Complex Proportional Assessment
EDAS	Evaluation based on Distance from Average Solution
MCDM	Multi-Criteria Decision-Making
NDA	Negative Distance from Average
PDA	Positive Distance from Average
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje

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