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Suitability Site Selection of LNG Refueling Stations along Pinglu Canal Based on GIS and Combination Weighting Method

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ABSTRACT

With the official opening of the Pinglu Canal, the core backbone project of the New Western Land-Sea Corridor, the demand for clean energy refueling infrastructure for inland shipping has increased sharply. Liquefied Natural Gas (LNG), as a low-carbon and efficient ship fuel, has become the main direction for the green transformation of inland shipping. However, the current site selection of LNG refueling stations along inland rivers faces problems such as single evaluation dimension, strong subjectivity in weight determination, and lack of spatial quantitative analysis. To address these issues, this paper constructs a suitability evaluation index system for LNG refueling stations along the Pinglu Canal from four dimensions: waterway and navigation conditions, market demand conditions, resource and infrastructure conditions, and safety and environmental conditions. A combination weighting model integrating Analytic Hierarchy Process (AHP) and Entropy Weight Method (EWM) is established to determine the index weights, which effectively balances the subjectivity of expert judgment and the objectivity of data information. Combined with Geographic Information System (GIS) spatial analysis technology, the single-factor raster layers are superimposed and analyzed to obtain the comprehensive suitability distribution map of LNG refueling stations. The results show that the highly suitable areas for LNG refueling stations along the Pinglu Canal are mainly concentrated in the Qinzhou Port section, Luwu Town section and Xijin Reservoir area of Hengzhou, accounting for 4.2%, 2.5% and 2.0% of the total study area respectively (totaling 8.7% of the total region). Finally, 5 optimal alternative sites are proposed, which can provide scientific decision-making basis for the planning and construction of LNG refueling infrastructure along the Pinglu Canal.

KEYWORDS

Pinglu Canal; LNG Refueling Station; Site Selection; GIS; Combination Weighting Method.

1. INTRODUCTION

The Pinglu Canal, with a total length of 134.2 km, is the first large-scale canal connecting the Xijiang River system and the Beibu Gulf in China. It is constructed according to the Class I inland waterway standard and can navigate 5,000-ton bulk carriers, with a designed annual one-way capacity of 89 million tons. After its completion at the end of 2026, it will shorten the shipping distance from Nanning to Qinzhou Port by about 560 km, becoming the most convenient sea passage for southwest China. With the rapid growth of cargo volume along the canal, the problem of high emissions from traditional diesel-powered ships has become increasingly prominent. In the context of the "dual

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carbon" goal, promoting the application of LNG-powered ships has become an inevitable choice for the green development of inland shipping along the Pinglu Canal.

The construction of LNG refueling stations is the key infrastructure supporting the promotion of LNG-powered ships. Reasonable site selection can not only reduce construction and operation costs but also improve the safety and service efficiency of refueling stations. At present, domestic and foreign scholars have carried out a series of studies on the site selection of LNG refueling stations. Pan et al. (2024) analyzed the influencing factors of inland LNG refueling station site selection from macro and micro perspectives, and pointed out that waterway conditions, land resources and safety are the core factors[2]. Zhang et al. (2024) systematically reviewed the application of GIS-based multi-criteria decision analysis in energy facility site selection, which provided a solid methodological framework for this study[4]. However, most existing studies use a single weighting method, which either overemphasizes the subjective experience of experts or ignores the actual characteristics of regional development, leading to deviations in evaluation results. In addition, there is still a lack of targeted research on the site selection of LNG refueling stations along the newly built Pinglu Canal.

To fill the above research gaps, this paper proposes a suitability site selection method for LNG refueling stations along the Pinglu Canal based on GIS and combination weighting method. The main contributions are as follows: (1) Construct a four-dimensional evaluation index system suitable for inland river LNG refueling stations, covering navigation, market, infrastructure and safety factors; (2) Establish a combination weighting model integrating AHP and EWM, which effectively improves the scientificity of weight determination; (3) Carry out empirical research based on the actual data of the Pinglu Canal, and propose specific optimal site selection schemes, which can provide technical support for the planning and construction of green shipping infrastructure along the canal.

2. STUDY AREA AND DATA SOURCES

2.1. Study Area Overview

The study area covers the entire Pinglu Canal and its 5 km buffer zone on both sides, starting from Pingtang Estuary of Xijin Reservoir in Hengzhou City, Nanning, and ending at Qinzhou Port sea area in Qinzhou City, spanning 3 cities and 6 counties (districts) in Guangxi. The terrain along the canal is relatively flat, with an average elevation of 20-60 m, and the river regime is stable after regulation. According to the freight volume prediction, the cargo throughput of the Pinglu Canal will reach 50 million tons in 2030 and 80 million tons in 2035, of which bulk cargo such as coal, ore and building materials accounts for more than 70%. The huge cargo volume will generate strong demand for LNG fuel, and it is estimated that the annual LNG demand for ships along the canal will exceed 300,000 tons by 2035.



Figure 1. *Geographical location and scope of the study area*

2.2. Data Sources and Preprocessing

The data used in this study include spatial geographic data and socio-economic data, as shown in Table 1. All spatial data are unified to the WGS84 coordinate system, and converted into raster data with a resolution of 100 m × 100 m through the resampling tool in ArcGIS 10.8. The socio-economic data are spatially interpolated to generate continuous raster layers, which are convenient for subsequent superposition analysis.

Table 1. Data sources and types

Data type	Specific content	Data source
Basic geographic data	Administrative boundary, water system, road network	National Geomatics Center of China (2025)
Waterway data	Pinglu Canal channel grade, water depth, shoreline stability	Guangxi Transportation Department (2025)
Topographic data	DEM data (30 m resolution)	Geospatial Data Cloud
Land use data	Land use type, construction land distribution	Resource and Environment Science and Data Center
Socio-economic data	GDP, population density, port cargo volume	Guangxi Statistical Yearbook (2025)
POI data	Residential areas, industrial parks, dangerous goods sites	Amap Open Platform
Planning data	Pinglu Canal overall planning, port layout planning	Guangxi Development and Reform Commission

3. CONSTRUCTION OF EVALUATION INDEX SYSTEM

Table 2. Evaluation index system for suitability of LNG refueling stations

Index layer	Index attribute	Assignment standard
Channel grade (C1)	Positive	Class I: 5 points, Class II: 4 points, Class III: 3 points, below Class III: 1 point
Shoreline stability (C2)	Positive	Stable: 5 points, basically stable: 3 points, unstable: 1 point
Distance to main port (C3)	Negative	<5 km: 5 points, 5-15 km: 3 points, >15 km: 1 point
Water depth condition (C4)	Positive	>6 m: 5 points, 4-6 m: 3 points, <4 m: 1 point
Port cargo volume (C5)	Positive	≥10 million tons/year: 5 points, 5-10 million tons/year: 3 points, <5 million tons/year: 1 point
Number of industrial parks within 10 km (C6)	Positive	>5: 5 points, 3-5: 3 points, <3: 1 point
Population density (C7)	Positive	>500 people/km^2: 5 points, 200-500 people/km^2: 3 points, <200 people/km^2: 1 point
Distance to LNG receiving station (C8)	Negative	<100 km: 5 points, 100-200 km: 3 points, >200 km: 1 point
Road accessibility (C9)	Positive	Adjacent to expressway: 5 points, adjacent to national highway: 3 points, only county road: 1 point
Construction land availability (C10)	Positive	Sufficient available land: 5 points, general: 3 points, scarce: 1 point
Distance to residential area (C11)	Positive	>100 m: 5 points, 50-100 m: 3 points, <50 m: 1 point
Distance to drinking water source protection area (C12)	Positive	Outside the protection area: 5 points, secondary protection area: 2 points, primary protection area: 0 point

Based on the relevant national standards such as Code for Design of Liquefied Natural Gas Terminals and Code for Design of Inland Liquefied Natural Gas Refueling Station Terminals, combined with the actual characteristics of the Pinglu Canal, this paper constructs a suitability evaluation index system for LNG refueling stations from four criterion layers: waterway and navigation conditions, market demand conditions, resource and infrastructure conditions, and safety and environmental conditions. The system consists of 4 criterion layers and 12 index layers. Specifically:

Waterway and navigation conditions (B1) include channel grade (C1), shoreline stability (C2), distance to main port (C3) and water depth condition (C4); Market demand conditions (B2) include port cargo volume (C5), number of industrial parks within 10 km (C6) and population density (C7); Resource and infrastructure conditions (B3) include distance to LNG receiving station (C8), road accessibility (C9) and construction land availability (C10); Safety and environmental conditions (B4) include distance to residential area (C11) and distance to drinking water source protection area (C12). The detailed index attributes and assignment standards are shown in Table 2.

4. COMBINATION WEIGHTING AND GIS EVALUATION MODEL

4.1. Combination Weighting Model

Multi-criteria decision-making methods combined with GIS have been widely applied in energy infrastructure planning and spatial suitability evaluation. The combination weighting method integrating AHP and Entropy Weight Method has been proven to be the most effective technique for balancing subjective and objective information[5,7,8,9,10], and has been successfully applied in inland river LNG refueling station site selection[6] and inland waterway transportation planning[1,3].

To overcome the shortcomings of single weighting method, this paper adopts the combination weighting method integrating AHP and EWM. AHP is used to determine the subjective weight reflecting expert experience, and EWM is used to determine the objective weight reflecting data information. The final combination weight is obtained by multiplying the subjective and objective weights and normalizing them.

4.1.1. AHP Subjective Weight Calculation

The steps of AHP are as follows:

Construct the judgment matrix. According to the 1-9 scale method, experts in the fields of shipping, energy and safety are invited to compare the importance of indicators pairwise, and construct the judgment matrix $A = (a_{ij})_{n\times n}$, where a_{ij} represents the importance ratio of index i to index j.

Calculate the weight vector. The maximum eigenvalue λ_{max} and the corresponding eigenvector W of the judgment matrix are calculated, and the eigenvector is normalized to obtain the subjective weight vector $W_A = (w_{A1}, w_{A2}, \ldots, w_{An})^T$.

Consistency test. Calculate the consistency index $CI = \frac{\lambda_{max}-n}{n-1}$ and the consistency ratio $CR = \frac{CI}{RI}$, where RI is the average random consistency index. When $CR < 0.1$, the judgment matrix passes the consistency test.

4.1.2. EWM Objective Weight Calculation

The steps of EWM are as follows:

Standardize the original data. For positive indicators:

$$r_{ij} = \frac{x_{ij}-min(x_j)}{max(x_j)-min(x_j)} \quad (1)$$

For negative indicators:

$$r_{ij} = \frac{max(x_j) - x_{ij}}{max(x_j) - min(x_j)} \quad (2)$$

where x_{ij} is the original value of the j-th index in the i-th evaluation unit, $max(x_j)$ and $min(x_j)$ are the maximum and minimum values of the j-th index respectively.

Calculate the proportion of the i-th evaluation unit in the j-th index:

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \quad (3)$$

where m is the number of evaluation units.

Calculate the information entropy of the j-th index:

$$e_j = -k \sum_{i=1}^{m} p_{ij} \, ln(p_{ij}) \quad (4)$$

where $k = \frac{1}{ln(m)}$, and when $p_{ij} = 0$, define $p_{ij} ln(p_{ij}) = 0$.

Calculate the objective weight:

$$w_{Ej} = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \quad (5)$$

4.1.3. Combination Weight Calculation

The combination weight is calculated by the multiplication synthesis method, which can better reflect the joint effect of subjective and objective information:

$$w_j = \frac{w_{Aj} \cdot w_{Ej}}{\sum_{j=1}^{n} w_{Aj} \cdot w_{Ej}} \quad (6)$$

where w_j is the final combination weight of the j-th index.

4.2. GIS Spatial Evaluation Model

The GIS spatial evaluation model is used to realize the visualization and quantitative analysis of site selection suitability, and the specific steps are as follows:

Generate single-factor raster layers. According to the assignment standard in Table 2, each index is assigned a value of 1-5 points, and the corresponding single-factor raster layer is generated in ArcGIS.

Weighted superposition analysis. Using the Weighted Sum tool in ArcGIS, the single-factor raster layers are superimposed according to the combination weights to obtain the comprehensive suitability score raster layer. The calculation formula is:

$$S = \sum_{j=1}^{n} w_j \cdot C_j \quad (7)$$

where S is the comprehensive suitability score, and C_j is the score of the j-th index.

Reclassification. Using the Natural Breaks (Jenks) method, the comprehensive suitability score is divided into five grades: highly suitable (4-5 points), relatively suitable (3-4 points), moderately suitable (2-3 points), relatively unsuitable (1-2 points) and unsuitable (0-1 point).

5. EMPIRICAL ANALYSIS AND RESULT DISCUSSION

5.1. Calculation of Index Weights

According to the above method, the subjective weight, objective weight and combination weight of each index are calculated respectively, as shown in Table 3. It can be seen that the top three indexes in combination weight are channel grade (0.1725), port cargo volume (0.1646) and distance to

drinking water source protection area (0.1479), which indicates that navigation conditions, market demand and environmental safety are the most important factors affecting the site selection of LNG refueling stations along the Pinglu Canal.

Table 3. Calculation results of index weights

Index	AHP subjective weight	EWM objective weight	Combination weight
C1	0.1082	0.1520	0.1725
C2	0.0824	0.0860	0.0978
C3	0.0878	0.0730	0.0832
C4	0.0737	0.0550	0.0620
C5	0.1200	0.1450	0.1646
C6	0.0949	0.0610	0.0696
C7	0.0698	0.0320	0.0364
C8	0.0596	0.0470	0.0529
C9	0.0494	0.0290	0.0324
C10	0.0455	0.0170	0.0197
C11	0.0800	0.0540	0.0610
C12	0.1286	0.1290	0.1479

5.2. Single-Factor Suitability Evaluation

According to the assignment standard, the single-factor suitability evaluation of each index is carried out, and the corresponding raster layers are generated.

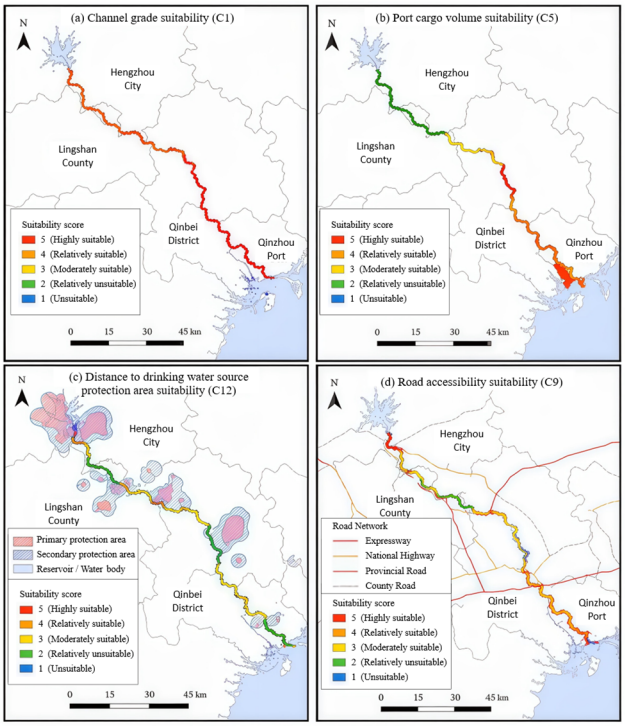


Figure 2. *Single-factor suitability evaluation maps*

It can be seen from Figure 2 that: (1) The entire main channel of the Pinglu Canal is Class I waterway, with good navigation conditions, and the highly suitable areas are concentrated in the straight sections with stable shorelines; (2) The port cargo volume is the highest in the Qinzhou Port section, followed by the Luwu Town section and Hengzhou section, which is consistent with the layout of industrial parks along the canal; (3) The drinking water source protection areas are mainly distributed in the upper reaches of the Qinjiang River and the Xijin Reservoir area, and these areas are strictly prohibited from building LNG refueling stations; (4) The road accessibility is the best in the Qinzhou Port area, followed by the areas along the Nanning-Qinzhou Expressway.

5.3. Comprehensive Suitability Evaluation

The single-factor raster layers are superimposed according to the combination weights to obtain the comprehensive suitability distribution map of LNG refueling stations along the Pinglu Canal, as shown in Figure 3.

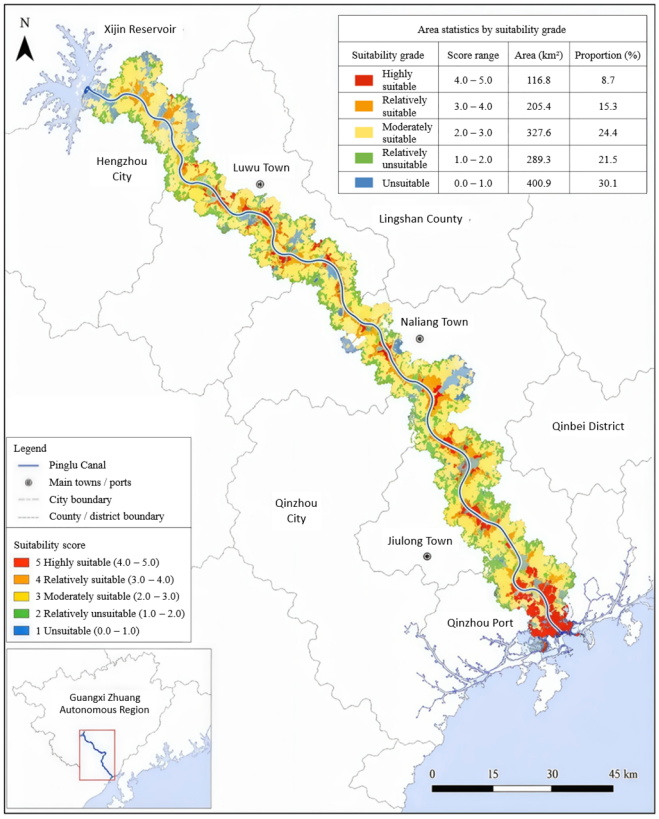


Figure 3. *Comprehensive suitability evaluation map of LNG refueling stations*

The statistical results of each suitability grade area are shown in Table 4. The highly suitable areas account for 8.7% of the total study area, mainly distributed in the Qinzhou Port section (4.2%), Luwu Town section (2.5%) and Xijin Reservoir area of Hengzhou (2.0%). These areas have the advantages of good navigation conditions, large market demand, perfect infrastructure and high safety, and are the preferred locations for building LNG refueling stations. The relatively suitable areas account for 15.3%, which can be used as reserve sites. The unsuitable areas account for 30.1%, and the relatively unsuitable areas account for 21.5%. The two together account for 51.6%, mainly including drinking water source protection areas, residential concentrated areas and unstable shoreline sections. This distribution pattern is consistent with the strict environmental protection requirements for LNG refueling stations.

Table 4. Statistical results of suitability grade areas

Suitability grade	Score range	Area (km^2)	Proportion (%)
Highly suitable	4.0-5.0	116.8	8.7
Relatively suitable	3.0-4.0	205.4	15.3
Moderately suitable	2.0-3.0	327.6	24.4
Relatively unsuitable	1.0-2.0	289.3	21.5
Unsuitable	0.0-1.0	400.9	30.1

5.4. Optimal Site Selection Scheme

Combined with the comprehensive suitability evaluation results and the actual planning of the Pinglu Canal, 5 optimal alternative sites are selected from the highly suitable areas, as shown in Figure 4. The basic information of each site is shown in Table 5.

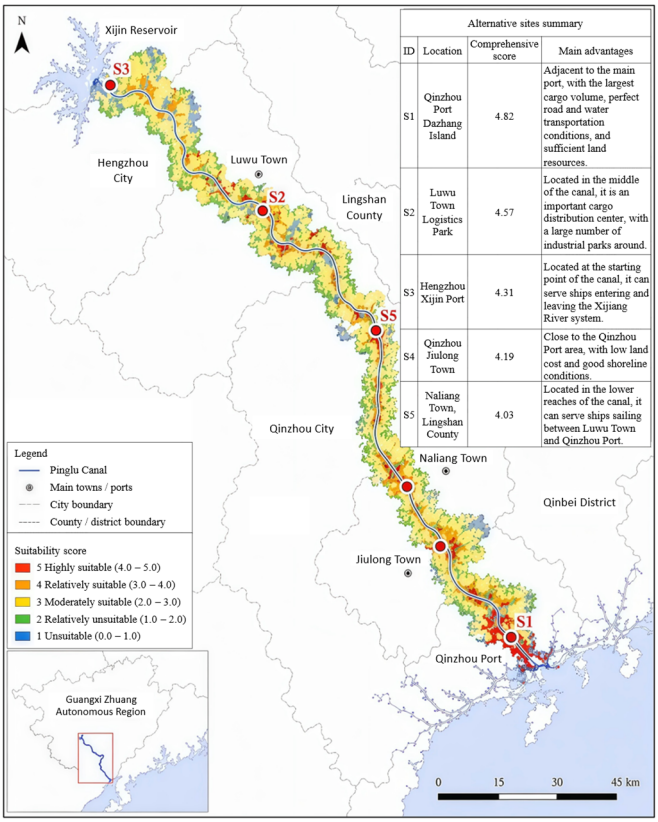


Figure 4. *Distribution map of optimal alternative LNG refueling stations*

The above 5 sites are evenly distributed along the 134.2 km Pinglu Canal, with an average spacing of 30-35 km. This spacing is far less than the 1,000 km cruising range of 5,000-ton LNG-powered ships, ensuring no refueling blind spots along the entire canal. Among them, S1 and S2 should be constructed first as core refueling stations, and S3, S4 and S5 can be constructed in stages according to the growth of cargo volume.

Sensitivity analysis was conducted by adjusting the weights of the top three indicators (C1, C5, C12) by ±10%. The results show that the ranking of the five alternative sites remains unchanged, indicating that the site selection scheme is robust and not sensitive to minor changes in index weights.

Table 5. Basic information of optimal alternative sites

Site number	Location	Comprehensive score	Main advantages
S1	Qinzhou Port Dazhang Island	4.82	Adjacent to the main port, with the largest cargo volume, perfect road and water transportation conditions, and sufficient land resources
S2	Luwu Town Logistics Park	4.57	Located in the middle of the canal, it is an important cargo distribution center, with a large number of industrial parks around
S3	Hengzhou Xijin Port	4.31	Located at the starting point of the canal, it can serve ships entering and leaving the Xijiang River system
S4	Qinzhou Jiulong Town	4.19	Close to the Qinzhou Port area, with low land cost and good shoreline conditions
S5	Naliang Town, Lingshan County	4.03	Located in the lower reaches of the canal, it can serve ships sailing between Luwu Town and Qinzhou Port

6. CONCLUSION AND PROSPECT

6.1. Conclusion

This paper constructs a suitability evaluation index system for LNG refueling stations along the Pinglu Canal, and proposes a site selection method based on GIS and combination weighting method. The empirical results show that:

The combination weighting method integrating AHP and EWM can effectively balance the subjectivity of expert judgment and the objectivity of data information, and improve the scientificity and rationality of index weight determination.

The highly suitable areas for LNG refueling stations along the Pinglu Canal are mainly concentrated in the Qinzhou Port section, Luwu Town section and Xijin Reservoir area of Hengzhou, accounting for 8.7% of the total study area.

The 5 optimal alternative sites proposed in this paper are evenly distributed along the canal, with good navigation conditions, large market demand and high safety, which can meet the refueling needs of LNG-powered ships along the Pinglu Canal in the next 10-15 years.

6.2. Prospect

This study still has some limitations: (1) The static evaluation method is adopted, and the dynamic changes of cargo volume and LNG demand in the future are not considered; (2) The economic factors such as construction cost and operation cost of refueling stations are not included in the evaluation system. In the future research, a multi-objective optimization model considering dynamic demand and economic cost can be constructed to further improve the accuracy and practicability of the site selection scheme.

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