frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 14 January 2026
DOI 10.3389/fmars.2025.1748630

OPEN ACCESS

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RECEIVED 18 November 2025
REVISED 06 December 2025
ACCEPTED 15 December 2025
PUBLISHED 14 January 2026

CITATION
Fu K, Ma J, Zhou L, Liu X, Gou Y, He M, Zhang S, Bian D and Guo J (2026) Integrated assessment of ecological environment quality in the eastern coastal zone of Hainan Island (China) using GIS and the analytic hierarchy process. *Front. Mar. Sci.* 12:1748630. doi: 10.3389/fmars.2025.1748630

Integrated assessment of ecological environment quality in the eastern coastal zone of Hainan Island (China) using GIS and the analytic hierarchy process

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Introduction: The core eastern coastal cities of Qionghai and Wanning on Hainan Island are facing escalating pressures on their ecological integrity and biodiversity due to intensifying human activities.
Methods: To evaluate the regional ecological environmental quality, this study established a comprehensive assessment framework based on a systematic analysis of local ecological-geological conditions. Multiple factors across topographic, geologic, hydrologic, pedologic, and anthropogenic dimensions—including topography, stratigraphy, water and soil quality, land use, and ecosystem type—were integrated. Using the Delphi method to determine factor weights and ArcGIS for spatial analysis.
Results: The assessment revealed that human activity is the dominant influence. The area was classified into four ecological quality categories: excellent, good, moderate, and poor. Notably, key coastal aquaculture zones such as Wancheng Town, Dongao Town, and Xiaohai Bay in Wanning were identified as having relatively poor ecological quality.
Discussion/conclusion: Consequently, future coastal management must prioritize regulating ecological risk in human-disturbed areas, enhancing pollution control in aquaculture, and strengthening land-use policies to foster sustained regional ecological improvement.

KEYWORDS

analytic hierarchy process (AHP), ArcGIS technology, coastal zone, ecological environment quality index, ecological environmental quality assessment, Hainan Island

1 Introduction

Coastal zones represent critical interfaces where global ecosystems and socioeconomic systems most intensively interact. The ecological and environmental quality (EEQ) of these regions is vital for maintaining biodiversity, ensuring ecological security, and supporting sustainable development (Banu, 2021; Guo and Wang, 2024). The evaluation of ecological environmental quality can be traced back to the ecological risk assessments conducted in the 1960s (Song et al., 2013). Subsequently, this field has garnered significant attention from Chinese scholars, leading to further refinement and development of the concept (Li, 1997; Ye and Liu, 2000; Zhou, 2000). However, under the combined pressures of global climate change and intensive human activities, coastal ecosystems are confronting severe challenges—including climate warming, sea-level rise, sharp declines in biodiversity, and the erosion and siltation of coastlines (Sun et al., 2024; Chen et al., 2024; Ahmed and Tamim, 2025). These threats underscore the urgent need for scientifically sound and comprehensive assessments of coastal EEQ to inform effective ecological conservation and spatial planning strategies.

The concept of ecological environmental quality (EEQ) reflects the overall capacity of an ecosystem to maintain its structure and function under natural and anthropogenic pressures, serving as a crucial indicator of the balance between environmental protection and socio-economic development (Wang et al., 2025a). Initially focused on pollutant risks, EEQ assessment has evolved into a comprehensive practice integrating natural, environmental, and socio-economic factors (Cai et al., 2023). The emergence of geographic information systems (GIS) (Johnson, 1990; Xiong et al., 2007), remote sensing (RS) (Kennedy et al., 2014; Liu et al., 2024; Wang et al., 2024a), and analytic hierarchy process (AHP) techniques (Saaty, 1977; Chen et al., 2008) has significantly advanced EEQ evaluation, enabling the spatially explicit analysis of complex ecological processes.

Hainan Island, the largest tropical island in China, hosts along its eastern coast the cities of Qionghai and Wanning. These cities form part of the eastern urban cluster in Hainan's Territorial Spatial Plan, with Qionghai designated as a key regional central city (Bai et al., 2025). Our study focuses on the terrestrial segment of the administrative region extending from Changpo Town in Qionghai to Liji Town in Wanning. This corridor is rich in natural resources and represents the "golden coastline" of Hainan's tourism sector, yet it also exhibits some of the most acute conflicts between human development and ecological preservation on the island. Previous research has laid important groundwork. Li et al. (2025) assessed ecological changes across the entire island, while Peng et al. (2018) developed a comprehensive evaluation index system for the central mountainous region. Notably, existing investigations have largely concentrated on specific marine ecosystems, such as Shimei Bay in Qionghai (Jia et al., 2012; Li et al., 2014; Yuan et al., 2023) and Xiaohai Lagoon in Wanning (Zhou et al., 2017; You et al., 2019; Zhong et al., 2025; Mutethya et al., 2025). Terrestrial studies remain scarce, with only limited work on vegetation or shoreline dynamics (Wang et al., 2022; Su et al., 2023; Wang et al., 2025b). Consequently, high-resolution, integrated assessments of the terrestrial environment in this rapidly developing coastal corridor —synthesizing multi-source geospatial and survey data—are still lacking. This gap hinders a holistic understanding of the region's eco-environmental status and limits the scientific basis for its sustainable management.

For the purpose of this study, which integrates geological conditioning factors, we employ this term to encompass the integrated state of the surface ecosystem and its underlying geological and pedological foundations. Today, the evaluation emphasizes ecosystem integrity, stability, and sustainability, aiming to provide scientific support for environmental management, ecological restoration, and regional sustainable development (Wang et al., 2025b; Wang et al., 2025c). This study aims to fill this gap by developing an integrated GIS-AHP framework to assess the EEQ of the eastern coastal zone of Hainan Island. Publicly available statistical datasets from relevant governmental departments, together with field-survey data on soil and water quality, were integrated to construct an evaluation system comprising eleven indicators. The specific objectives were to: (1) quantify the relative importance of key ecological factors using the Delphi-AHP method; (2) map the spatial heterogeneity of EEQ; and (3) identify the primary drivers of ecological degradation, providing a scientific basis for targeted coastal management.

2 Data sources and the evaluation system

2.1 Study area

Qionghai and Wanning are located along the eastern coast of Hainan Island (Figure 1) and serve as the core cities within the eastern development cluster of the Hainan Free Trade Port. The permanent venue of the Boao Forum for Asia is situated in this region, granting it significant importance both within China and globally. The study area is characterized by a tropical monsoon climate, with strong monsoonal influence, abundant sunshine, high temperatures, and heavy rainfall. Typhoons occur frequently, and there is no distinct division of the four seasons, but rather a clear alternation between dry and wet seasons. The persistently warm and humid conditions create favorable circumstances for crop growth. However, uneven rainfall distribution often results in droughts and floods, while wind-related disasters (such as Qingming winds, dry hot winds, typhoons, and autumn cold winds) and cold damage caused by low-temperature and cloudy–rainy weather exert additional adverse effects on agricultural production. Topographically, the terrain of the study area slopes from west to east, comprising mainly medium- and low-elevation erosional mountains, denudation hills, undulating erosional plains, basalt platforms, marine depositional landforms, and fluvial erosion–accumulation features. Driven by government policies, population growth, and rapid economic development, the

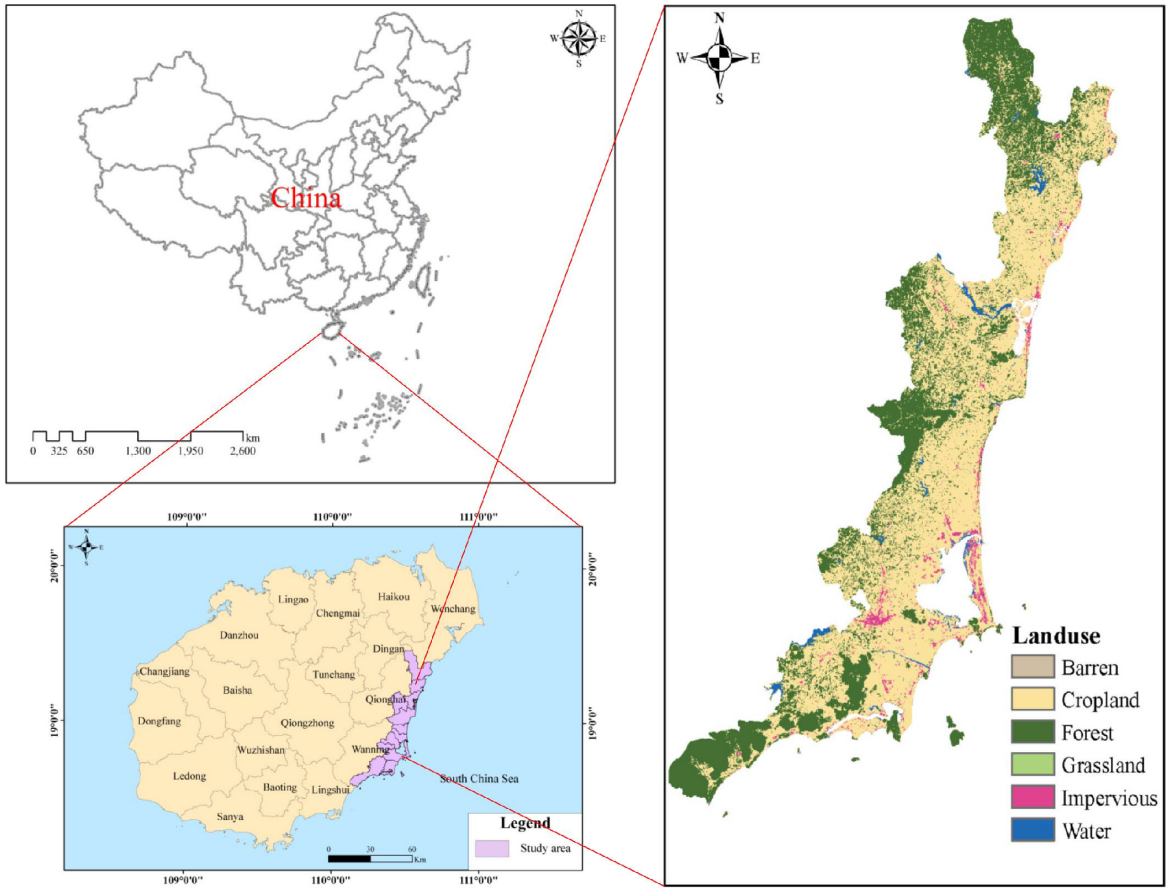

FIGURE 1
Location of the study area.

intensity of human activities in the region has increased markedly, placing growing pressure on the local ecological environment.

The study area currently confronts significant ecological and environmental challenges, primarily driven by intensified socioeconomic development. The principal issues include water eutrophication, shoreline erosion and sedimentation, ecological degradation from mining and landfill operations, soil erosion (notably riverbank collapse), land desertification, and heavy metal contamination in soils. These problems are particularly acute in the coastal zone, where unsustainable management of high-elevation aquaculture ponds has triggered seawater intrusion, soil and sediment contamination, and degradation of aquatic environments, ultimately leading to water quality deterioration and lagoon shrinkage. Seawater intrusion has elevated chloride concentrations beyond permissible limits, posing a tangible threat to freshwater resources in coastal areas. The rapid expansion of large-scale marine aquaculture has further exacerbated the problem, causing contamination of surface and groundwater, abandonment of domestic wells, salinization of farmland, and increasing soil desertification. As a result, the natural self-regulatory capacity of the coastal ecosystem has been substantially weakened - or even disrupted - and adjacent coral reef systems have suffered severe degradation, reflecting extensive ecological damage across the region.

2.2 Data source

The data used in this study primarily comprise spatial and statistical datasets. The spatial data include administrative boundary maps and base geographic maps of eastern Hainan Island. The statistical data encompass eleven key parameters: stratigraphy and lithology, slope, land use type, surface water quality, groundwater quality, soil quality, soil type, population density, and ecosystem type, among others. Specifically, topographic and geomorphological data were derived from a digital elevation model (DEM) with a spatial resolution of 2 meters. Stratigraphic and lithologic information was extracted from geological maps, while data on water and soil quality were obtained through laboratory testing and analytical measurements. The remaining datasets were acquired through field surveys and *in situ* observations. Details of the data sources are presented in Table 1.

2.3 Construction of an evaluation framework

Ecological and environmental quality is influenced by multiple interacting factors. Accordingly, this study developed an ecological environmental quality evaluation framework grounded in ecological–geological survey data. The framework integrates both the ecological and geological conditions of the region, as well as the natural geographical features and human activity characteristics of Qionghai and Wanning. Eleven evaluation indicators were selected to construct the assessment system, including topography and geomorphology, stratigraphy and lithology, soil type, parent material, land use, surface water quality, groundwater quality, soil quality, ecological–geological problems and geological hazards, human activity intensity, and ecosystem type. While "Land Use Type" and "Ecosystem Type" are derived from similar base data, they serve distinct purposes within the index system. "Land Use Type" is an indicator of anthropogenic pressure and management intensity, whereas "Ecosystem Type" serves as a proxy for intrinsic ecological structure, biodiversity potential, and natural resilience. This distinction ensures that both the human footprint on the landscape and the foundational ecological character are independently evaluated, avoiding a singular reliance on either socio-economic or purely natural classification.

The extent and intensity of the influence of these evaluation factors on ecological and environmental quality vary across the study area. Considering the regional characteristics, the Delphi method was employed to construct a hierarchical decision-making model encompassing all selected indicators (Wang et al., 2024b; Bagheri et al., 2024). Experts were invited to evaluate and score the relative importance of each factor in terms of its impact on local ecological environmental quality. Based on these scores, an A–B judgment matrix (Table 2) was established, followed by consistency testing and hierarchical ranking. The finalized judgment matrix was then used to determine the weight of each indicator. Subsequently, using the spatial statistical tools in ArcGIS, an Ecological Environmental Quality Index (EEQI) was developed through a weighted summation model integrating the eleven suitability evaluation factors. Prior to the weighted overlay, all single-factor raster layers were normalized to a common dimensionless scale (0-1) to eliminate unit differences and ensure comparability. The min-max normalization method was applied using the following formula:

$$I_{normalized} = \frac{I_i - I_{min}}{I_{max} - I_{min}}$$

This method was chosen for its simplicity and effectiveness in preserving the original relative relationships between scores within each factor. The calculation formula is as follows:

$$A = \sum_{i=1}^{n} I_i W_i$$

Note:where A represents the comprehensive ecological environmental quality index of the study area; I_i denotes the value of the i-th evaluation indicator; and W_i is the corresponding weight assigned to indicator i.

TABLE 1 Data sources.

Type	Sources	Types
Administrative division map of the eastern part of Hainan Island	Geographic Information Sharing Platform (http://www.tianditu.gov.cn)	Spatial data
Basic geographic basemap	Geographic Information Sharing Platform(http://www.tianditu.gov.cn)	Spatial data
stratigraphic lithology	1:50,000 Regional Geological Survey Report	Basic geological data
Slope	2-meter grid data model(DEM) (2019)	Spatial data
land use type	Classification data of land cover in Hainan Province(2020)	Statistical data
Surface water quality	This study measured	Statistical data
Groundwater quality	This study measured	Statistical data
Soil quality data	This study measured	Statistical data
Soil type data	This study measured	Statistical data
Population density data	Statistical yearbooks of cities and counties in the study area	Statistical data
ecosystem type	This study measured	Statistical data
Geological Hazard Data	This study measured	Statistical data
Soil parent material data	This study measured	Statistical data

To ensure the objectivity of the indicator weights, a Delphi method involving a panel of 15 experts was employed. The experts were selected from disciplines of ecology, geology, pedology, environmental science, and GIS. The consultation process consisted of two rounds. In the first round, experts independently scored the factors. The results were aggregated by calculating the arithmetic mean and standard deviation. These statistics, along with anonymous expert comments, were then fed back to the panel in the second round for re-scoring. The final weights were determined as the geometric mean of the second-round scores. This iterative and anonymous procedure helped reduce individual bias and build a robust consensus.

As shown in Table 2, the calculated values are $\lambda = 11.1845$, CI = 0.1440, RI = 1.49, and CR = 0.01 < 0.10. Since the consistency ratio (CR) is less than 0.10, the judgment matrix demonstrates good consistency, indicating that the constructed matrix is reasonable and the derived weights are reliable. The consistency ratio (CR = 0.01) confirms the logical coherence of the expert judgments. The derived weights (Table 2) reveal a clear hierarchy of influence among the factors. Ecological and Geological Problems and Hazards (C9, weight = 0.197) emerged as the most influential

TABLE 2 Judgment matrix and hierarchical ranking table of ecological environment quality evaluation.

A	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	w^T	Sorting
C1	1	0.5	1	0.3	0.5	0.2	0.2	0.2	0.1	0.3	0.2	0.02309	11
C2	2	1	2	0.5	1	0.3	0.2	0.3	0.2	0.3	0.3	0.03525	9
C3	1	0.5	1	0.3	0.5	0.2	0.2	0.2	0.1	0.3	0.2	0.02309	10
C4	3	2	3	1	2	0.5	0.3	0.5	0.5	1	0.5	0.06968	7
C5	2	1	2	0.5	1	0.3	0.3	0.3	0.3	0.5	0.3	0.04229	8
C6	5	4	5	2	3	1	1	1	0.5	2	1	0.12795	3
C7	6	5	6	3	3	1	1	2	1	2	2	0.16918	2
C8	5	4	5	2	3	1	0.5	1	0.3	2	1	0.11579	5
C9	7	5	7	2	4	2	1	3	1	3	2	0.19736	1
C10	4	3	4	1	2	0.5	0.5	0.5	0.3	1	0.5	0.07618	6
C11	5	4	5	2	3	1	0.5	1	0.5	2	1	0.12014	4

The calculated eigenvalue and consistency test results are as follows: $\lambda = 11.1845$, CI = 0.1440, RI = 1.49, and CR = 0.01 < 0.10, indicating that the consistency of the judgment matrix satisfies the acceptance criterion. The factors C_1–C_{11} correspond respectively to: topography and geomorphology (C_1), stratigraphy and lithology (C_2), soil type (C_3), parent material of soil formation (C_4), land use (C_5), surface water quality (C_6), groundwater quality (C_7), soil quality (C₈), ecological and geological problems and hazards (C_9), intensity of human activities (C_{10}), and ecosystem type (C_{11}).

factor, underscoring that existing environmental degradation (e.g., water pollution, soil erosion) and geological vulnerability are the most direct constraints on ecological quality in this coastal region. This is followed closely by factors representing the current environmental state: Groundwater Quality (C7, 0.169) and Surface Water Quality (C6, 0.128), highlighting the critical role of water resources. Factors related to human pressure (Human Activity Intensity C10 and Land Use C5) and the ecological template (Ecosystem Type C11) also carry substantial weight (0.076–0.120), reflecting the significant impact of anthropogenic activities and the inherent resilience of ecosystems. In contrast, the fundamental geological and pedological background factors (Topography C1, Lithology C2, Soil Type C3, Parent Material C4) received the lowest weights (0.023–0.070), indicating that while they form the foundational matrix, their influence on current ecological quality is more indirect and subordinate to the pressures and states captured by the higher-ranked factors. This weight distribution aligns well with the study area's context, where acute anthropogenic and biophysical pressures are driving ecological change.

Based on the ArcGIS software platform, the administrative boundaries of Qionghai and Wanning in eastern Hainan Island were used as the base map. Spatial overlay analysis and attribute spatialization were conducted using the collected datasets and the corresponding weights of each evaluation factor. A multi-factor comprehensive evaluation map was then generated to delineate the ecological environmental quality zones within the study area. Specifically, the eleven single-factor evaluation maps of the Qionghai–Wanning coastal zone were converted into raster layers, and spatial weighted overlay calculations were performed according to the weights presented in Table 2. Finally, the composite results were classified into different ecological environmental quality grades following the established classification criteria.

2.4 Delineation of assessment units

The evaluation unit serves as the fundamental information carrier in ecological environmental quality assessment. Common methods for delineating evaluation units include the grid method, buffer zone method, and vector polygon method. In this study, the grid method was selected for spatial unit division. Comprehensive analysis of the study area's topography, geomorphology, meteorological conditions, and land-use types revealed that the terrain is relatively gentle, with spatially uniform patterns of rainfall and temperature. Additionally, both stratigraphic–lithologic features and land-use distribution exhibit regular spatial continuity. To balance spatial detail with computational efficiency in this regional assessment, a grid size of 220 m × 220 m was selected. This resolution aligns with the effective scale of primary input datasets—such as the land use/cover classification—ensuring that each unit captures relevant spatial heterogeneity. Considering the spatial extent of the study area, the grid method was applied to divide it into evaluation units of 220 m × 220 m. Each grid cell was treated as an independent information carrier for assessing the ecological environmental vulnerability index, which was subsequently classified to obtain the overall ecological environmental quality assessment results of the study area.

3 The evaluation process and its outcomes

3.1 Single factor evaluation result

3.1.1 Topography and geomorphology

The slope of the study area was derived from a 2 m DEM and classified into four grades (Table 3). The resulting evaluation map

TABLE 3 Slope grading table.

Slope range	Assigned score	Area(km^2)	Proportion of study area	Rationale
0°-5°	1	845.0870628	0.644259	Highly suitable for agriculture and settlement.
5°-15°	3	344.4988306	0.262632	Gentle undulations, moderate suitability.
15°-25°	5	86.11825143	0.065653	Mountainous/Hilly regions, limited human activity.
>25°	7	36.01460304	0.027456	Prohibited cultivation zones, poor ecological conditions.

(Figure 2A) shows a clear spatial pattern: the extensive coastal plains and river terraces (slopes 0°-5°), which are hubs of human activity and agriculture, received the most favorable scores. In contrast, the steeper mountainous areas in the west (slopes >25°), characterized by sparse vegetation and minimal human presence, were assigned the poorest scores, effectively delineating the region's fundamental ecological constraints.

3.1.2 Stratigraphy and lithology

Based on engineering geological properties, the stratigraphy and lithology were categorized into four groups, with scores assigned according to their weathering resistance and implications for soil development (Table 4). The spatial distribution of these scores (Figure 2B) reveals that the Quaternary alluvial plains and platforms, composed of loose sediments, form the foundation of the highest quality ecological areas. Conversely, the regions underlain by granite and other hard rocks, which produce thin and nutrient-poor soils, correlate strongly with areas of higher ecological vulnerability.

3.1.3 Soil type

Variations in soil-forming factors and pedogenic processes result in differentiation of soil properties, leading to the formation of diverse soil types with distinct morphological characteristics. Different soils have varying compositions and properties, which in turn exert different effects on ecological environmental quality. Based on the soil environmental assessment, soils such as yellow soils, volcanic ash soils, red soils, calcareous soils, paddy soils, and lateritic soils have high nutrient content, favoring vegetation growth and reflecting relatively good ecological environmental quality. In contrast, alluvial soils with moderate nutrient content, coastal sandy soils with poor fertility, and rocky or saline–alkaline soils unsuitable for cultivation exhibit progressively lower suitability for plant growth, sparser surface vegetation, and reduced ecological quality. Using the soil type distribution map of Hainan Island as the base dataset, the study area was updated and each soil type was assigned a grade score. These values were processed to generate the soil type-based single-factor ecological environmental quality map (Figure 3A).

3.1.4 Soil parent material

Soil parent material, derived from the weathering of surface rocks, consists of loose fragments whose physical properties have been altered to form unconsolidated weathered material. It serves as the primary source of soil and mineral nutrients for plants, making it a fundamental factor influencing ecological environmental quality. The characteristics of parent material include porosity, permeability, and the presence of soluble mineral nutrients, which can initially support only lower plants and microbial growth. As lower plants and microorganisms undergo metabolic cycles and accumulate organic matter, the parent material gradually develops fertility, providing suitable conditions for higher plant growth and promoting its transformation into soil. Therefore, the influence of soil parent material on ecological environmental quality is not solely determined by the original rock type but is also closely linked to vegetation cover. Based on the combined relationships among vegetation, soil, and parent material in the study area (Table 5), and through comprehensive analysis of the spatiotemporal characteristics of ecological environmental quality, a single-factor evaluation map for soil parent material was generated (Figure 3B).

3.1.5 Land use

Land use type is determined by human activities such as agricultural production, afforestation, and urban development. In the study area, six main land use types were identified: dryland, forest land, irrigated paddy fields, grassland, construction land, and water/wetland areas. Different land use types exert varying impacts on ecological environmental quality, reflecting differences in vegetation cover, soil disturbance, water consumption, and habitat conditions. These land use data were processed in ArcGIS and assigned scores according to their influence on ecological environmental quality, contributing to the land use-based single-factor evaluation map of the Qionghai–Wanning coastal zone.

Land use type affects ecological vulnerability primarily through three aspects: the ecological suitability of the land use type, stability, and spatial pattern (Wang et al., 2022; Niu et al., 2024). Numerous studies have shown that fragmentation of land patches and reductions in mean patch size increase their susceptibility to external disturbances, leading to greater isolation between habitat patches, local species extinctions, and reduced landscape stability. Moreover, land use type plays a critical role in supporting ecological functions, including the production of biological resources, water storage and retention, mitigation of extreme hydrological events such as droughts and floods, soil conservation and erosion control, wind and sand prevention, prevention of desertification and salinization, microclimate regulation, carbon dioxide absorption and oxygen generation, air and water purification, biodiversity protection and maintenance, as well as disaster prevention and mitigation (Liu et al., 2021; Feng et al., 2023).

Six land use types were identified and scored based on their ecological functionality and associated human disturbance levels (Table 6). The single-factor evaluation map (Figure 4A) highlights a

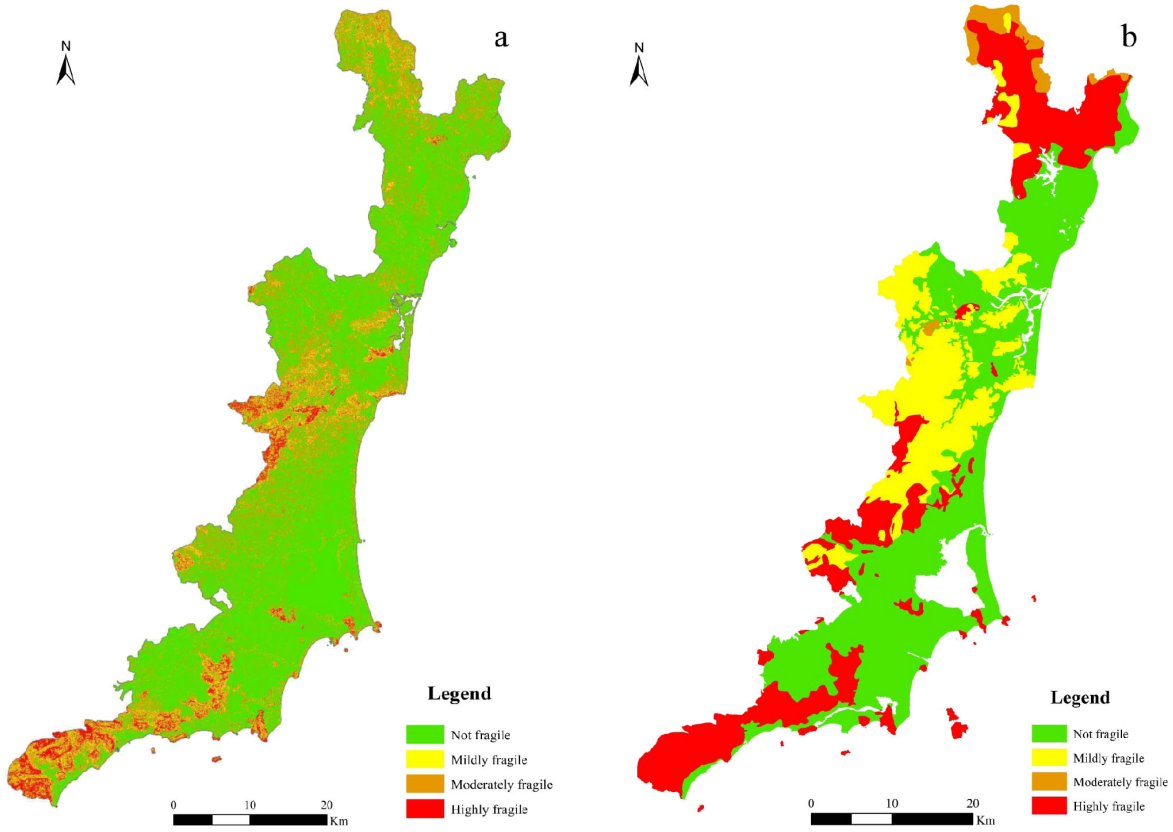

FIGURE 2
The single-factor evaluation map of topography **(A)** and lithology **(B)**.

critical conflict: the ecologically most stable land covers (forests, wetlands) are predominantly located in the central and western parts, while the most disturbed areas (construction land) are concentrated along the coast and in urban centers, directly mapping the footprint of intense anthropogenic pressure on the landscape.

3.1.6 Surface water quality

According to the "Environmental Quality Standards for Surface Water" (GB 3838, 2002), surface water bodies are classified into five categories based on environmental function and protection objectives (Table 7). The results reveals a concerning pattern of degraded water quality (Classes IV-V) in the coastal lagoons and certain river sections, particularly adjacent to aquaculture zones and urban centers. This pattern provides direct evidence of the influence of localized anthropogenic discharges on the aquatic ecosystem. Based on field sampling and laboratory analysis, a single-factor eco-environmental quality map derived from surface water quality was generated (Figure 4B).

3.1.7 Groundwater quality

According to the "Groundwater Quality Standard" (GB/T 14848, 2017), groundwater is classified into five categories based on chemical composition, current groundwater quality, and potential human health risks, considering the requirements for domestic, industrial, and agricultural water use. The detailed classification and scoring criteria provided in Table 8.

The groundwater quality data obtained from field sampling and laboratory analysis were classified according to the aforementioned standards, and subsequently used to generate the single–factor ecological environmental quality map based on groundwater quality (Figure 5A).

3.1.8 Soil quality

Soil quality was evaluated by integrating the risk control standards for both construction land (GB 36600, 2018) and agricultural land (GB 15618, 2018). The classification and scoring criteria derived from these standards are systematically presented in Table 9.

TABLE 4 Stratigraphy and lithology grading table.

Stratigraphy and lithology	Assigned score	Rationale
Loose rocks	1	Quaternary sediments
Interbedded soft-hard rock groups	3	Sandstone-shale
Moderately hard rock groups	5	Volcanic rocks
Hard rock groups	7	Granite

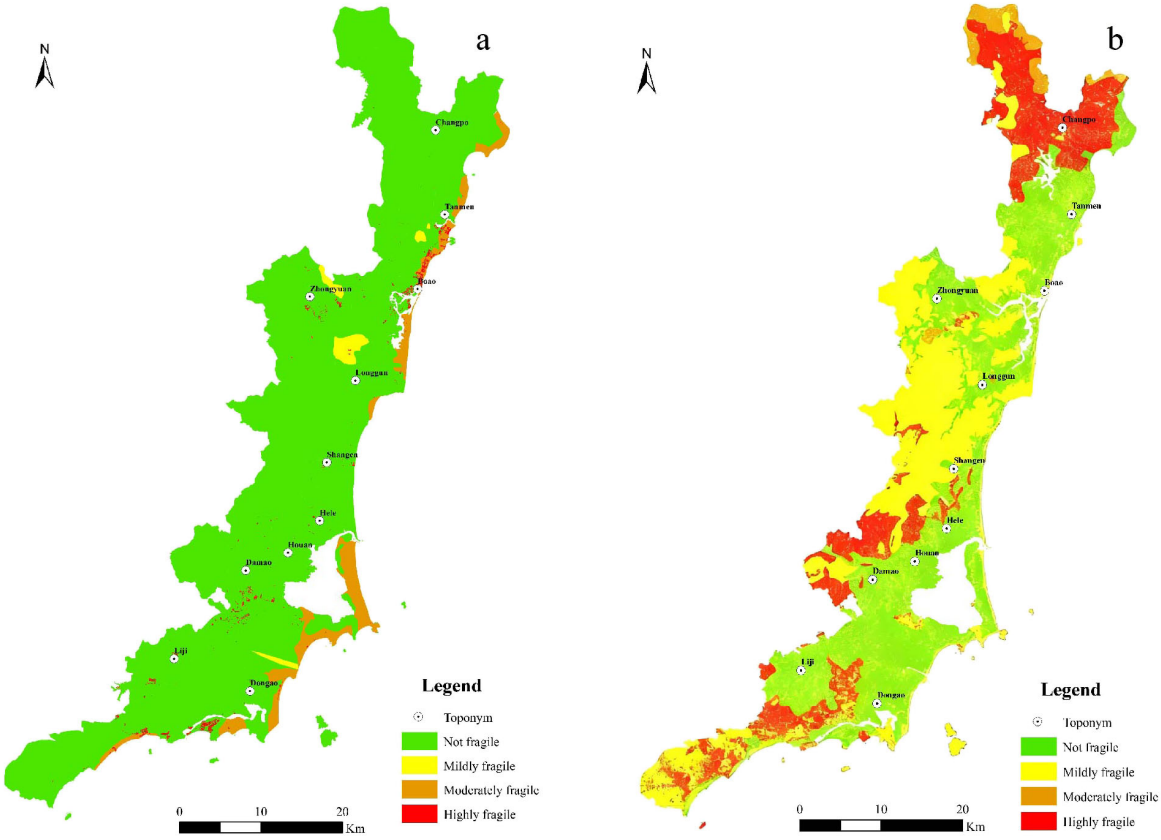

FIGURE 3
The single-factor evaluation map of soil type **(A)** and soil parent material **(B)**.

The single–factor soil quality map (Figure 5B) was generated by applying this scoring system to the land use dataset. The resulting spatial distribution reveals distinct contamination hotspots, primarily corresponding to industrial zones and areas of intensive agricultural activity, indicating where soil pollution poses the most significant risk to local ecological security and land –use sustainability.

3.1.9 Ecological–geological issues and geological hazards

Based on ecological–geological surveys, the primary ecological and environmental problems in the study area include water pollution (from agricultural irrigation and marine aquaculture) and soil contamination (notably heavy metal pollution). The main geological hazards comprise soil erosion, land desertification, landslides, collapses, and debris flows. Both types of factors significantly influence ecological environmental quality. Therefore, using the severity of ecological–geological issues and the susceptibility to geological hazards as single-factor indicators for ecological–geological vulnerability evaluation is appropriate.

In ArcGIS, the geological hazard susceptibility zoning map of Qionghai and Wanning (Hainan Provincial Geological Survey Institute, 2015, slightly modified) was used as the base dataset. Grading and scoring were applied according to the classification standards for ecological–geological problem severity and geological hazard susceptibility (Table 10), resulting in the single-factor

TABLE 5 Vulnerability classification of soil parent material.

Quality grade	Excellent	Good	Moderate	Poor
Vegetation type	crops	Forest	Low shrubs	Sparse or minimal vegetation
Soil type	Paddy soil, lateritic soil	Lateritic soil	Lateritic soil, alluvial soil	Coastal sandy soil
Soil parent material	Quaternary alluvial and colluvial weathered material	Jurassic–Cretaceous bedrock weathered material, Triassic bedrock weathered material	Weathered material of intermediate igneous rocks	Marine sediment in coastal areas
Assigned score	1	3	5	7

TABLE 6 Vulnerability classification of soil parent material.

Land use type	Assigned score	Rationale
Forest Land, Water/ Wetland	1	High ecological suitability, strong stability
Grassland, Irrigated Paddy fields	3	Moderate ecological function
Dryland	5	Subject to human disturbance
Construction Land	7	High fragmentation, strong human disturbance

evaluation map for ecological–geological vulnerability, including ecological–environmental issues and geological hazards, for the study area (Figure 6A).

3.1.10 Human activity intensity

The population density of Hainan Island remains relatively low, exerting limited pressure on the environment. Using population density as the base dataset and considering the actual population distribution, a four-level classification system—Excellent, Good, Moderate, and Poor—was applied, with the "Poor" level not set due to the low overall density. Using townships as the basic evaluation units, the classification criteria were as follows: population density ≤ 400 persons/km², rated as Excellent and assigned a score of 1; 400–800 persons/km², rated as Good and assigned a score of 3; 800–1200 persons/km², rated as Moderate and assigned a score of 5; >1200 persons/km², rated as Poor and assigned a score of 7. Based on population data from the Qionghai and Wanning Statistical Yearbook (2020), the human activity intensity single-factor evaluation map was generated (Figure 6B).

3.1.11 Ecosystem type

The ecosystem types in the study area were classified based on habitat characteristics and species composition into five major categories: forest ecosystems (I), wetland ecosystems (II), grassland ecosystems (III), farmland ecosystems (IV), and urban ecosystems (V). The "buffer" function, as an ecological service, differs across ecosystem types. Forest ecosystems clearly provide the strongest buffering function, followed by wetland and grassland ecosystems, then farmland ecosystems, with urban ecosystems providing the weakest buffering function. Accordingly, ecosystem type was used as a single-factor indicator for ecological–geological vulnerability, with values assigned as 1, 3, 5, and 7, respectively, in ascending order of vulnerability. It is acknowledged that this classification is broad, and future studies would benefit from incorporating more granular metrics such as landscape pattern indices.

In ArcGIS, land use/land cover data derived from remote sensing interpretation for Qionghai and Wanning were used as

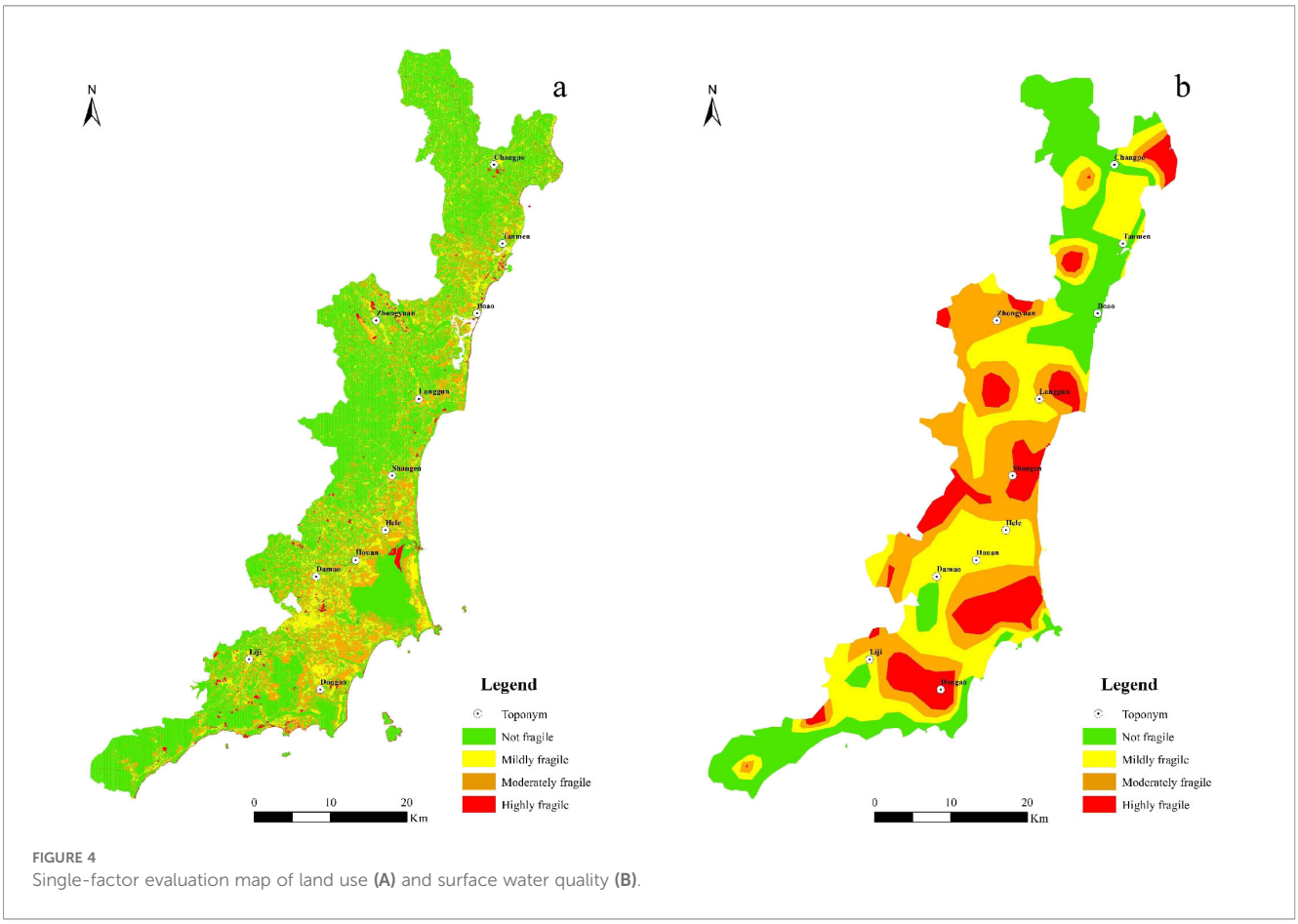

FIGURE 4
Single-factor evaluation map of land use **(A)** and surface water quality **(B)**.

TABLE 7 Stratigraphy and lithology grading table.

Surface water quality	Assigned score	Rationale
Class I/II	1	Excellent ecological quality
Class III	3	Good quality
Class IV	5	Moderate quality
Class V	7	Poor quality

the base dataset. Data were classified according to ecosystem type and assigned values according to the grading system, generating the single-factor evaluation map for ecosystem type in ecological–geological vulnerability for the study area (Figure 7).

3.2 Comprehensive evaluation

Using a geographic information system, the eleven single-factor ecological environmental quality maps of the eastern coastal zone of Hainan Island were converted into raster format. Each raster layer was weighted according to the factor weights presented in Table 11 and spatially integrated using a weighted summation approach to calculate the Ecological Environmental Quality Index (EEQI) for each evaluation unit. The EEQI values were classified into four grades (Superior, Satisfactory, Moderate, Substandard) using the equal-interval method. This method was chosen for its objectivity, reproducibility, and the clear, fixed thresholds it provides, which are advantageous for environmental monitoring and communicating findings to stakeholders in management and planning contexts. The resulting comprehensive ecological environmental quality map of the study area is presented in Figure 8.

3.3 Analysis of spatial correlations among evaluation factors

Beyond individual factor assessments, analyzing the spatial correlations among factors is crucial for understanding their synergistic effects on overall ecological quality. A visual comparison of the single-factor maps (Figures 2-7) reveals several pronounced spatial association patterns:

TABLE 8 Groundwater quality grading table.

Groundwater quality	Assigned score	Rationale
Class I/II	1	Suitable for all uses
Class III	3	Moderate quality
Class IV	5	Relatively high chemical concentrations
Class V	7	Poor quality, unsuitable as drinking source

Strong Positive Association (Co-occurrence of Stressors): The spatial distributions of poor groundwater quality (Figure 5A), poor surface water quality (Figure 4B), and high human activity intensity (Figure 6B) exhibit remarkable overlap. These factors collectively form a "coastal degradation complex" concentrated in aquaculture zones and urban peripheries, indicating that anthropogenic pressure drives concurrent deterioration in both surface and subsurface water environments.

Strong Negative Association (Mutual Exclusivity): The high-quality zones for soil (Figure 5B) and vegetation (inferred from Land Use/Ecosystem Type, Figures 4A and 7) are predominantly located in the western forested uplands, which coincide with areas of low human activity intensity and favorable topography (gentle slopes, Figure 2A). This inverse pattern highlights that preserved natural ecosystems are spatially segregated from major anthropogenic disturbances.

Underlying Geological Control: The distribution of less resistant rock types (e.g., loose sediments, Figure 2B) and certain soil parent materials (Figure 3B) provides a foundational template that correlates with the locations of fertile soils and, subsequently, with historical and current agricultural land use. This suggests a cascading influence from geology to pedology to land use.

These observed spatial correlations confirm that the driving factors do not operate in isolation. Instead, they form interlinked clusters—where human pressure clusters with environmental degradation, and natural stability clusters with favorable geological conditions. This interconnectedness reinforces the necessity of the integrated multi-factor approach employed in this study and helps explain the emergence of the distinct EEQI spatial pattern shown in Figure 8.

4 Discussion and conclusion

4.1 Discussion

We developed an integrated evaluation framework combining ArcGIS spatial analysis and the Analytic Hierarchy Process (AHP) to assess the ecological and environmental quality of the eastern coastal zone of Hainan Island. The model incorporates 11 key factors spanning topographic, geological, pedological, hydrological, ecological, and anthropogenic dimensions: topography and geomorphology, stratigraphic lithology, soil type, parent material, land use, surface water quality, groundwater quality, soil quality, ecological and geohazards, human activity intensity, and ecosystem type.

Our assessment reveals that the overall ecological condition of the region is generally favorable. Notably, areas classified as Superior account for 78.86% of the total, predominantly located in forested uplands with minimal human disturbance. The seemingly high proportion of 'excellent or good' area alongside the identification of human activity as the dominant driver is explained by the landscape's structure: acute human pressures are spatially confined to coastal and urban hotspots, while the favorable ratings are sustained by the extensive, less-disturbed forested and

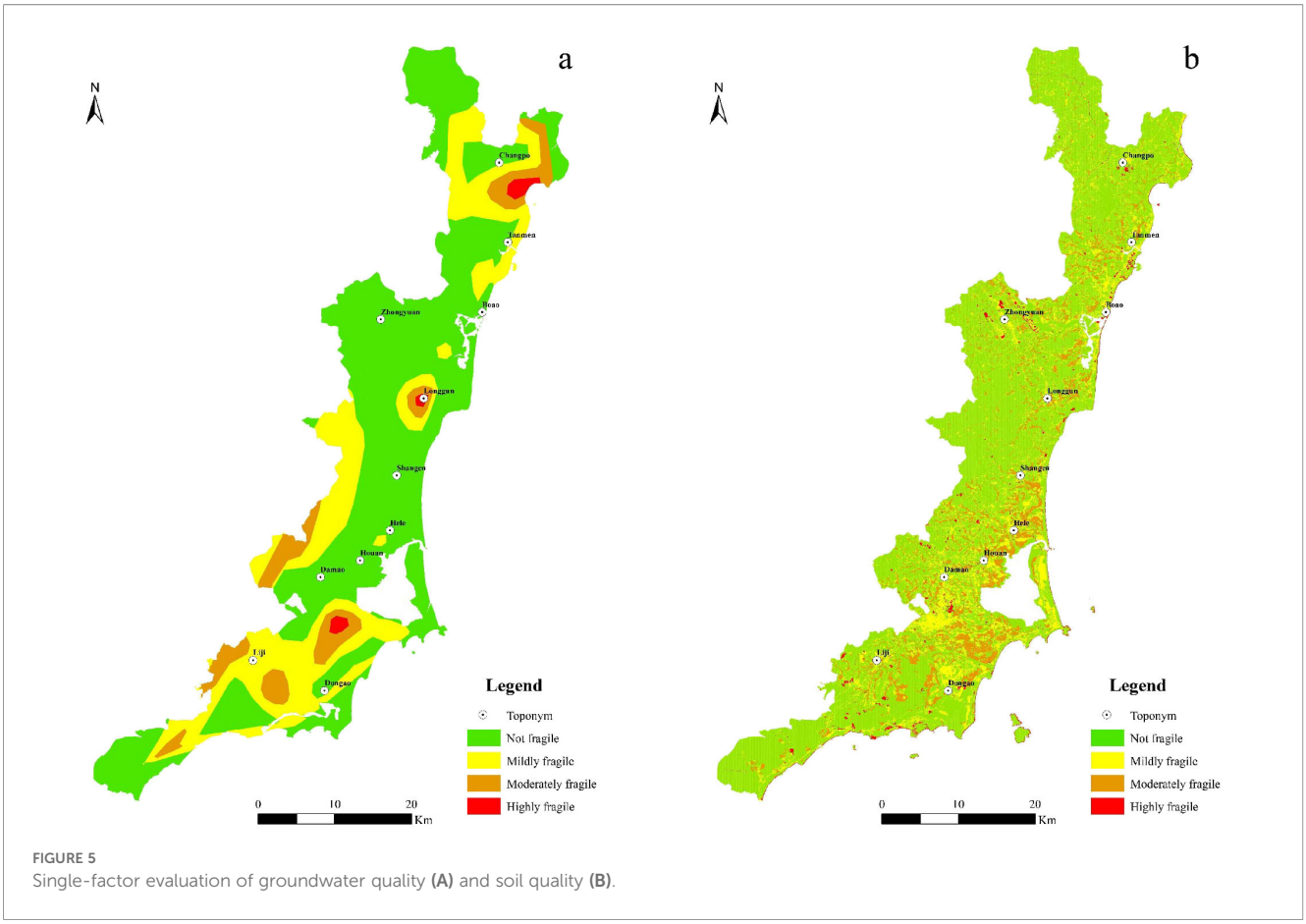

FIGURE 5
Single-factor evaluation of groundwater quality **(A)** and soil quality **(B)**.

agricultural lands that comprise most of the study area. This result is consistent with findings by Peng et al. (2018) in central Hainan, underscoring the robust natural ecological baseline shared across the island's eastern and central regions. While Peng et al. (2018) established a robust evaluation system for the island's predominantly natural, mountainous interior, our framework is explicitly designed for the human-nature interface of the coastal zone. By integrating direct anthropogenic pressure indicators (e.g., human activity intensity) with underlying geological vulnerabilities, we not only corroborate the location of high-quality refugia but also diagnose the processes creating sharp ecological gradients at the coast. Thus, we advance from a regional-scale state assessment to a management-scale process diagnostic, providing actionable insights for the island's most dynamically stressed ecological frontier. Satisfactory (12.52%) are mainly distributed throughout agricultural landscapes, where moderate human activity coexists with largely preserved ecosystem structures. In contrast, zones rated as Moderate (2.35%) and Unsatisfactory (6.27%), though limited in extent, exhibit pronounced spatial clustering that strongly correlates with intense anthropogenic pressure-highlighting human

TABLE 9 Soil quality grading table.

Land category	Risk threshold & corresponding score	Description/Included land types
Category I (Sensitive)	Screening value: Score = 1	school land, healthcare and social welfare facility land, community/children's parks in public green spaces.
–	Control value: Score = 3	–
Category II (Less Sensitive)	Screening value: Score = 3	Industrial land, logistics and storage land, commercial service facility land, road and transportation land, public facility land, other public management and service land, green space and square land.
–	Control value: Score = 5	–
–	Exceeding control values of both categories: Score = 7	Applicable to both categories

TABLE 10 Classification standards for ecological environment problems and geological hazards.

Eco-environmental issues	The degree of susceptibility to geological disasters		
	Not-prone	Low-prone	Moderately-prone
Ecologically stable	1	3	5
Ecologically degraded	3	5	7

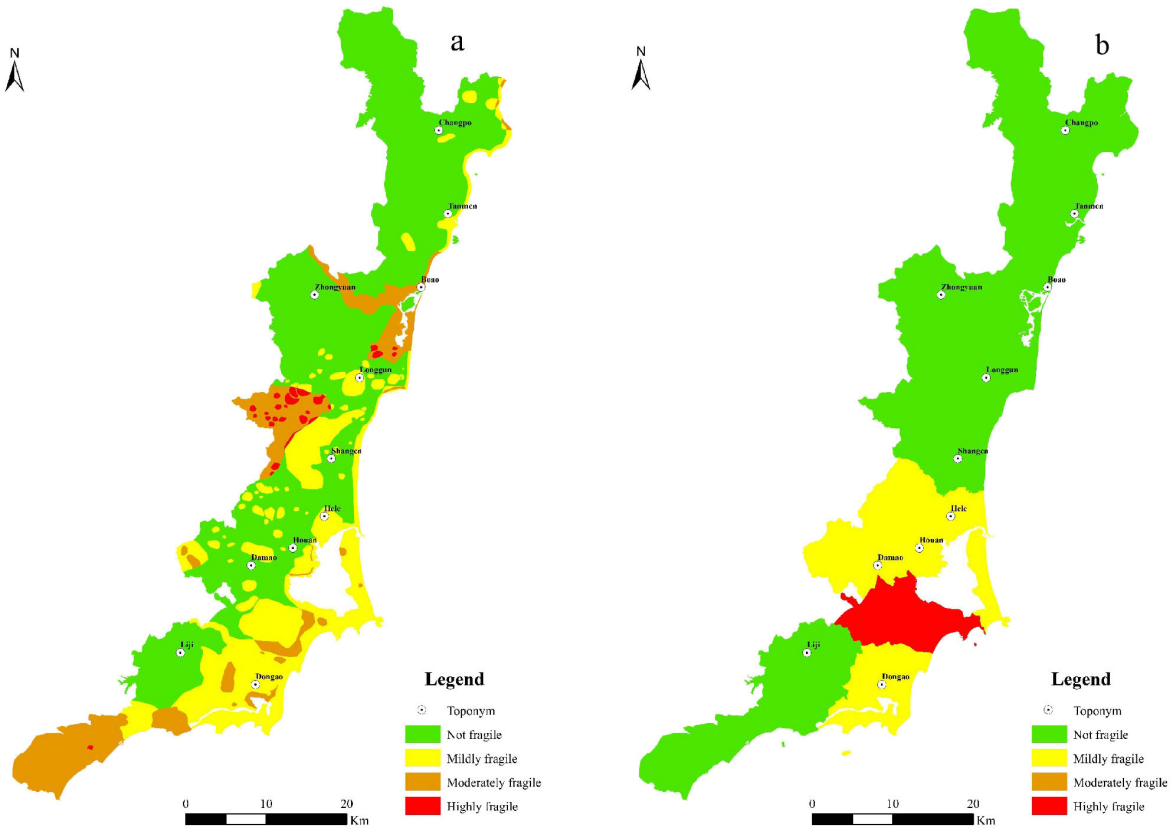

FIGURE 6
Single-factor evaluation of ecological environment problems and geological disasters **(A)** and human activity intensity **(B)**.

disturbance as a principal factor driving localized ecological degradation.

Spatial analysis reveals a distinct concentration of ecologically substandard areas within the coastal aquaculture and urban zones of Wancheng Town, Dong'ao Town, and Wanning Xiao Hai. This clustered distribution reflects systematic environmental pressures driven by three interconnected factors: Geologically, these regions are characterized by poorly consolidated sediments and interbedded soft-hard rock strata with low weathering resistance, establishing an inherently vulnerable ecological foundation. Remotely sensed and land-use data further demonstrate concentrated built-up areas, diminished vegetation cover, and pronounced landscape fragmentation-factors that collectively compromise ecosystem integrity and resilience. Furthermore, population densities exceeding 1,200 persons/km^2 sustain intensive anthropogenic activities, notably expansive agriculture and large-scale mariculture, which have persistently degraded soil structure and fertility while amplifying eutrophication, soil salinization, and sediment contamination. This finding aligns with Ma et al. (2025), who documented intensifying human pressure across Hainan Island, and further refines the conclusion by Yu et al. (2024) that anthropogenic disturbance is a critical driver of ecological quality-specifically pinpointing coastal urban and aquacultural zones as priority areas for ecological risk management.

4.2 Limitations and future work

The integrated evaluation framework developed in this study, combining the Analytic Hierarchy Process (AHP) with GIS-based spatial overlay analysis, successfully synthesizes multi-source geospatial data at a 1:50,000 scale to systematically assess the complex coastal ecosystem. This methodology proves both applicable and operationally viable for regional environmental diagnosis. Nevertheless, several limitations should be acknowledged. Certain input data—particularly geological hazard susceptibility—were derived from historical surveys, and their limited temporal resolution may affect the accurate capture of dynamic environmental processes. Furthermore, while surface water quality interpolation was applied across the study area to serve as a continuous influence layer within the overlay model, future studies could employ more hydologically explicit methods, such as confining interpolation to water bodies and modeling land-based influence through defined buffer zones or dispersion models. Additionally, while the 220 m × 220 m evaluation unit was selected based on data compatibility and regional assessment needs, a systematic scale-sensitivity analysis was not conducted. Exploring the impact of different grid resolutions on the assessment outcomes would strengthen the methodological robustness in future applications. Moreover, although the Delphi method was used to

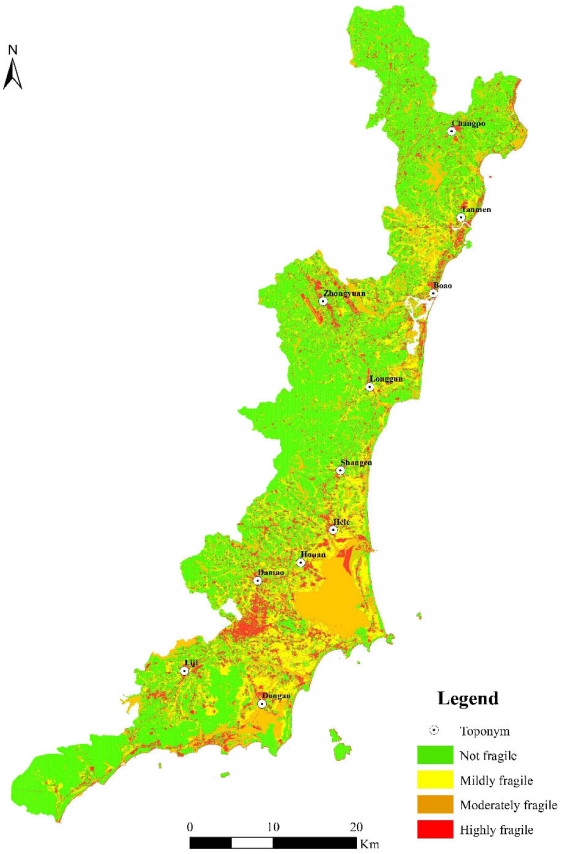

FIGURE 7
Single-factor evaluation map of ecosystem types.

consolidate expert knowledge in factor scoring and weight determination, some inherent subjectivity remains in the valuation process. The ecosystem type classification, while informative, is a broad categorization. Future studies would benefit from incorporating more granular metrics such as landscape pattern indices (e.g., patch density, connectivity) or direct biodiversity assessments. To advance this research direction, future work should prioritize the integration of high-resolution remote sensing (e.g., Sentinel-2) to dynamically monitor indicators like NDVI and chlorophyll-a concentration and *in-situ* sensor networks to facilitate real-time monitoring and updating of critical parameters. The incorporation of machine learning approaches (e.g., Random Forest for feature importance ranking) also holds promise for refining the weight determination process, offering a pathway toward more adaptive, objective, and precise ecological assessment models.

4.3 Conclusions

1. The ecological and environmental quality of the eastern coastal zone of Hainan Island is generally favorable, with over 90% of the area classified as "Superior" and "Satisfactory", reflecting a stable regional ecosystem and robust ecological carrying capacity.
2. Significant spatial heterogeneity in ecological quality was observed, primarily driven by human activities. Intensive anthropogenic pressures—including urbanization, agricultural expansion, and mariculture-have led to notable degradation in localized areas.
3. The integrated evaluation framework developed in this study, based on ArcGIS and AHP, provides a applicable tool for meso-scale coastal ecological assessment and supports scientific decision-making in territorial spatial

TABLE 11 Statistical table of the classification of ecological environment quality index and the proportion of each evaluation level to the total area of the study area.

Level	Eco-environmental quality index(R)	Proportion to total area
Superior	R>0.75	78.86%
Satisfactory	0.50<R ≤ 0.75	12.52%
Moderate	0.25<R ≤ 0.50	2.35%
Substandard	R ≤ 0.25	6.27%

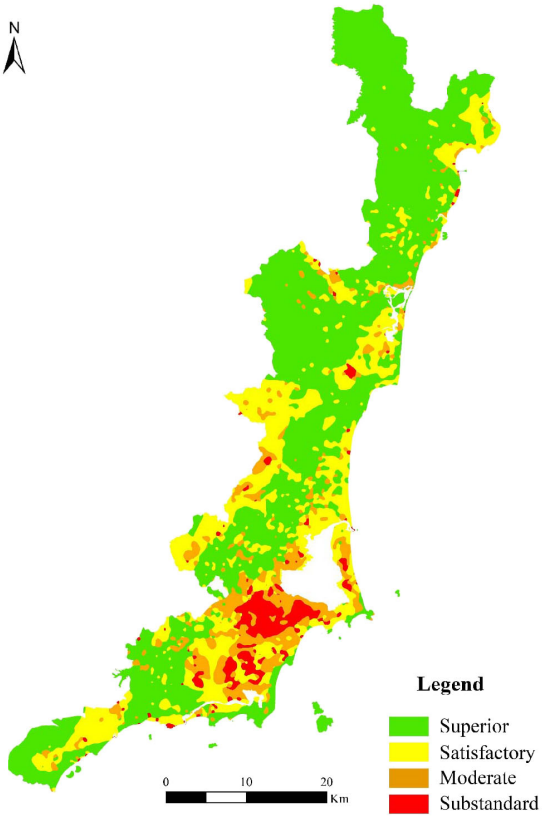

FIGURE 8
Evaluation map of ecological environment quality in the eastern coastal zone of Hainan Island.

planning, ecological conservation, and industrial layout optimization.

4. Moving forward, coastal management strategies should prioritize ecological risk regulation in human-disturbed areas and enhance pollution control in aquaculture zones. In particular, Wanning's Xiaohai Bay requires strengthened regulation of aquaculture intensity, improved wastewater treatment, and the establishment of ecological buffer zones, while Qionghai should emphasize compact and environmentally sensitive urban development to mitigate localized ecological degradation. Strengthening land-use regulation through these location-specific measures aligns with the ecological civilization and ecological security goals of the Hainan Free Trade Port and will further promote sustained improvement in regional ecological quality.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KF: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. JM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LZ: Data curation, Writing – original draft, Writing – review & editing, Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. XL: Data curation, Writing – original draft, Writing – review & editing. YG: Data curation, Writing – original draft, Writing – review & editing. MH: Data curation, Writing – original draft, Writing – review & editing. SZ: Writing – original draft, Writing – review & editing, Data curation. DB: Data curation, Writing – original draft, Writing – review & editing. JG: Formal Analysis, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. We acknowledge the financial support from the China Geological Survey Haicheng wen Coastal Natural Resources Comprehensive Survey Project (DD20240300306 (DD20230414)).

Conflict of interest

Author YG was employed by the company Guiyang Baiyun District Municipal Development and Construction Co., Ltd.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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