



Research Article

Development of A Composite Sustainability Index Within An Integrated Coastal Zone Management Framework: A Case Study of Ho Chi Minh City, Vietnam

Thanh-Minh Tran, Thi-Diem-Loan Tran, Minh-Luan Nguyen, Tan-Cuong Le*

Institute for Environment and Resources, Vietnam National University Ho Chi Minh City (VNU-HCM), Vietnam

*Corresponding Email: tancuong@hcmier.edu.vn, letancuongmttn@gmail.com

Abstract

Coastal regions are increasingly under compounded pressures from climate change and rapid socioeconomic development, and integrated approaches to sustainability assessment are needed. This study assesses coastal sustainability in Ho Chi Minh City by developing a composite sustainability index (CSI) structured around three key dimensions: socioeconomic, ecoenvironmental, and institutional management. An integrated coastal zone management (ICZM) framework was adopted to reorganize the index system, enhancing cross-dimensional linkages while explicitly clarifying the predominant role of the environmental dimension and the coordinating function of management. The CSI was quantified and spatially represented through the integration of multicriteria decision-making (MCDM), geographic information systems (GIS), and remote sensing. The results indicated that the CSI values ranged from 0.378 to 0.630, with half of the subareas falling within low to moderate levels, reflecting significant imbalances among the three dimensions. Although the eco-environmental component remained predominant (49%), the findings revealed clear trade-offs between economic growth and environmental quality. Overall, ecosystem degradation emerged as the primary driver of reduced sustainability, highlighting the need to prioritize mangrove conservation and restoration alongside strengthened environmental monitoring within an ICZM-based planning approach. Beyond the case study, the proposed CSI provides a transferable, spatially explicit ICZM-based framework to support sustainability assessment and evidence-based decision-making across coastal regions.

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Introduction

Coastal regions play a pivotal role in socioeconomic development, housing more than 40% of the global population (Zuo et al., 2025) and accounting for approximately 60% of global economic output (Liu et al., 2021). Owing to their strategic geographic locations and abundant natural capital, these regions have emerged as vital economic and trade hubs, driving globalization over the past few decades (Jing et al., 2026; Wu et al., 2021). However, coastal ecosystems are being increasingly exposed to intensifying pressures

from climate change and anthropogenic activities, including sea-level rise, erosion, rapid urbanization, resource overexploitation, and land-use change (Ahmadi et al., 2026; Hassan et al., 2026).

According to the Intergovernmental Panel on Climate Change (IPCC), the global mean sea-level rise rate reached 3.6 mm per year from 2006–2015, nearly double the 20th-century average, and is projected to continue rising throughout the 21st century (Intergovernmental Panel on Climate Change, 2019; 2021). The increasing frequency and intensity of extreme

events, such as tropical storms and storm surges, are exerting increasing pressure on coastal ecosystems, leading to shoreline erosion and a decline in ecosystem service provision (Hassan et al., 2026; Mafi-Gholami et al., 2026). These natural hazards are further compounded by rapid urbanization, industrialization, and other anthropogenic activities, which have intensified environmental degradation and undermined coastal sustainability (Cuong et al., 2023; Lin and Yu, 2018; Tao et al., 2025). Under these interacting pressures, recent extreme events have caused severe losses of life and property in coastal areas worldwide, including Typhoon Yagi (2024), which caused 320 deaths and USD 1.49 billion in damage in Vietnam (Ministry of Agriculture and Rural Development, 2024). In addition, mangrove conversion for aquaculture remains a major driver of forest loss, accounting for 20–35% of global mangrove decline and reducing coastal protection and resilience (Goldberg et al., 2020; Herbeck et al., 2020). Moreover, sea-level rise continues to increase flood risk in many coastal cities, which threatens long-term sustainability (Tay et al., 2022). These impacts underscore the urgent need for integrated management approaches to balance socioeconomic development and ecosystem conservation.

To address the complex challenges of coastal areas, integrated coastal zone management (ICZM) is recognized as a comprehensive approach that coordinates multisectoral conflicts (Zhang et al., 2024a). Unlike traditional models, which are often fragmented along administrative or sectoral boundaries, the ICZM promotes an integrated, ecosystem-based approach to sustainable development (Cicin-Sain and Knecht, 2013; Zhang et al., 2024a). ICZM emphasizes interdisciplinary coordination and stakeholder engagement and supports progress toward sustainable development goals (SDGs), particularly those of SDGs 11 and 14 (Areizaga et al., 2012; Puthucherril, 2022; Zhang et al., 2024a). However, despite being institutionalized and integrated into policy frameworks in many countries, the implementation of ICZM remains challenging (Gonçalves and Pinho, 2022; Mukherjee et al., 2025). In practice, short-term economic priorities, such as port expansion and industrial development, often outweigh the long-term value of ecosystem services (Ahmadi et al., 2026; Miao et al., 2025). Moreover, the lack of integrated quantitative assessment tools also limits its effectiveness in decision-making (Fu et al., 2026).

The need for objective tools to quantify coastal sustainability has led to the development of various index-based approaches. Existing studies range from eco-environmental health assessments using driver–pressure–state–impact–response (DPSIR) frameworks with dozens of indicators (Wan et al., 2024) or remote-

sensing indicators (Zhao et al., 2025) to socioeconomic indices that balance economic growth with ocean health (Ding and Tabeta, 2024; Wu et al., 2021). More recent studies have adopted comprehensive frameworks that integrate environmental, economic, social, and management-governance dimensions to assess coastal sustainability (de Alencar et al., 2020; Fu et al., 2026; Mafi-Gholami et al., 2026). Despite their increasing sophistication and comprehensiveness, a fundamental limitation of many existing studies lies in the fragmented integration of sustainability dimensions. In many frameworks, these dimensions are structured as parallel, independent indicator groups rather than as an integrated mechanism, leaving ICZM principles insufficiently embedded in sustainability assessment. In addition, many approaches rely on long-term, consistent datasets, which limits their practical applicability.

In addition to index development, various analytical methods have been proposed to integrate multiple dimensions in coastal sustainability assessment. Notably, multicriteria decision-making (MCDM) methods are widely applied to support sustainability evaluation and the construction of composite indices (Hussain et al., 2026; Tran et al., 2024; Tseng and Chiang, 2026). Conventional techniques, such as the analytic hierarchy process (AHP), analytic network process (ANP), and Delphi method, are often combined with the MCDM to increase the robustness of the results (Hamid-Mosaku et al., 2024; Khodadoust et al., 2026; Tran et al., 2024) but remain susceptible to subjective weight assignment and inconsistencies in expert judgment (Marzouk et al., 2024; Teng et al., 2025). To address these limitations, the group best–worst method (GBWM) has been proposed to reduce subjectivity and improve consistency and reliability in weight estimation (Khodadoust et al., 2026; Streimikis et al., 2024). Moreover, advances in remote sensing and geographic information systems (GISs) have enabled the acquisition of large-scale spatial data on land cover, mangroves, and climate change, providing a robust foundation for coastal sustainability assessment (Areizaga et al., 2012; Hassan et al., 2026; Tran et al., 2024; Zhao et al., 2025).

Despite increasing methodological sophistication, recent studies continue to reveal important theoretical gaps, particularly in how management (or governance) is conceptualized and integrated into quantitative frameworks. In many studies, management is represented through ICZM and treated as a fourth, standalone pillar alongside the three traditional dimensions of sustainability (de Alencar et al., 2020). However, this approach may lead to conceptual inconsistencies, as management functions not only as an independent dimension but also as a coordinating

and guiding mechanism for development processes (de Alencar et al., 2020; Zhang et al., 2024a). It directly shapes development outcomes through institutions, policies, and related instruments (Cavalheiro et al., 2025). Moreover, separating management as a standalone pillar may increase the complexity of index systems and create redundancy between policy-related indicators and those reflecting development outcomes (Fu et al., 2026; Nardo et al., 2005). Such overlap can induce high correlations among variables, leading to potential multicollinearity within the indicator system (Greco et al., 2019; Nardo et al., 2005). More importantly, this approach may obscure the core role of the ICZM as an integrated management framework that guides and regulates coastal development decisions (Areizaga et al., 2012; Cicin-Sain and Knecht, 2013; Gallagher, 2010). In many existing frameworks, management is often indirectly represented through qualitative policy indicators (Fu et al., 2026; Satumanatpan et al., 2017; Walling et al., 2024; Zhang et al., 2024a), while methodological approaches that explicitly integrate ICZM principles into sustainability index systems remain limited (Walling et al., 2024; Zuo et al., 2025).

Motivated by these gaps and practical needs, this study develops a composite sustainability index tailored to the coastal context of Ho Chi Minh City. Moving beyond the conventional four-pillar paradigm, it employs ICZM principles as a structuring framework to reconfigure the index system, explicitly positioning management as a coordinating mechanism across sustainability dimensions. This study further quantifies and spatializes the index by integrating MCDM (GBWM), GIS, and remote sensing, enabling direct application to coastal spatial planning and management. By providing a robust, data-driven decision-support tool, this research contributes to more integrated and sustainable long-term coastal development.

Materials and methods

1) Study area

The study area comprises 14 coastal communes of Ho Chi Minh City, located between 10°18'45"–10°39'37" N and 106°44'26"–107°34'15" E (Figure 1), and extends approximately 190–200 km along the coastline from An Thoi Dong to Binh Chau, representing one of Vietnam's most strategically important coastal zones (Ho Chi Minh City People's Committee, 2026). This river–sea interface features diverse geomorphologies, including sandy and muddy coasts, estuaries, tidal channels, and extensive mangrove ecosystems; notably, the Can Gio Mangrove Biosphere Reserve is recognized by UNESCO (Ho Chi Minh City People's Committee, 2026; Prime Minister of Vietnam, 2023; 2024). With a high population density (approximately 1,378 people per km²) (Ba Ria Vung Tau Statistical Office, 2025; Ho Chi Minh City

Statistical Office, 2025), the area plays a key economic role through aquaculture, fisheries, coastal industry, logistics, and tourism, contributing approximately 15% of local GRDP (Prime Minister of Vietnam, 2023; 2024). It is also a strategic focus for both marine economic development and mangrove conservation, highlighting the challenge of balancing economic growth with ecosystem protection (Ho Chi Minh City People's Committee, 2026). Rapid urbanization and land use change have been driven by its strategic location and natural resources, yet the area remains highly vulnerable to natural and anthropogenic pressures. Large-scale mangrove conversion for aquaculture and industry has reduced forest cover by more than 50% since 2003, weakening natural coastal protection (Ho Chi Minh City People's Committee, 2026). The area is also exposed to sea-level rise, coastal erosion, and extreme weather events (Ho Chi Minh City People's Committee, 2026; Prime Minister of Vietnam, 2023; 2024). These interacting pressures highlight the need for integrated management to support sustainable coastal development.

2) Methodology

In this study, an integrated ICZM-based framework that harmonizes the socioeconomic, eco-environmental, and institutional-management dimensions of coastal sustainability was proposed (Figure 2). MCDM, GIS, and remote sensing were applied to quantify the indicators and analyze spatial patterns of sustainability.

2.1) Development of criteria sets and corresponding weights

2.1.1) Development of criteria sets

MCDM methods were applied to develop a criteria system for three components: socioeconomic, eco-environmental, and institutional management. On the basis of sustainable development theory and the ICZM framework (Cicin-Sain and Knecht, 2013; de Alencar et al., 2020; Fu et al., 2026; Walling et al., 2024; Zhang et al., 2024a), a literature review was conducted to compile a preliminary set of assessment criteria, with the complete list provided in Supplementary Table S1. A purposive expert-sampling approach was then adopted to recruit experts with relevant expertise and familiarity with the study area. This approach is consistent with recent GBWM applications, which typically rely on focused expert panels to weight criteria (Dehshiri et al., 2022; Kotb et al., 2024). A total of 12 experts were selected and evenly distributed across the three components. The socioeconomic group included two experts from Vietnam National University, Ho Chi Minh City (VNU-HCM), and two from local authorities; the ecoenvironmental group included two experts from Ho Chi Minh City University of Technology (HCMUT) and two from the Institute for Environment and Resources (IER); and the institutional management group included

two experts from the Department of Agriculture and Environment and two from local authorities.

First-round expert consultation was conducted in person on October 6, 2025, at IER in Ho Chi Minh City. The questionnaire included the preliminary assessment criteria, which the experts evaluated using a binary response (selected/not selected). Criteria that received agreement from more than 50% of the panel were retained in the final set of criteria (Table 1) (Diamond et al., 2014). The experts also identified the best (*B*) and worst (*W*) criteria within each component, forming the basis for weight estimation using the GBWM.

2.1.2) Weight determination using the GBWM

A second round of expert consultation with the same 12 experts was conducted from November 3 to 7, 2025, with the GBWM questionnaires distributed to and returned by the experts via email. On the basis of the best (*B*) and worst (*W*) criteria identified in the first round, a GBWM pairwise comparison matrix was developed at both the criterion and component levels (Supplementary Table S2). Experts rated the preference of the best criterion over each criterion and of each criterion over the worst criterion using a 1–9 scale. On the basis of these conclusions, the optimal weights and their deviation ranges for the criteria and component indices were determined using the GBWM, as described in Eqs. 1–7 (Rezaei, 2016; Safarzadeh et al., 2018):

$$\text{Min } \text{Max}_k w'_k \mu_k = \text{Min}(\mu) \quad (\text{Eq. 1})$$

$$\mu \geq w'_k \mu_k, \forall k \in D \quad (\text{Eq. 2})$$

$$\left| \frac{w_B}{w_i} - a_{Bi} \right| \leq \mu_k, \forall i \in C, \forall k \in D \quad (\text{Eq. 3})$$

$$\left| \frac{w_i}{w_w} - a_{iW} \right| \leq \mu_k, \forall i \in C, \forall k \in D \quad (\text{Eq. 4})$$

$$\sum_{i \in C} w_i = 1 \quad (\text{Eq. 5})$$

$$w_i \geq 0, \forall i \in C \quad (\text{Eq. 6})$$

where w'_k denotes the weight of expert k in expert set D , with $w'_k \in (0,1)$ and $\sum_{k \in D} w'_k = 1$; w_B and w_w denote the weights of the best (*B*) and worst (*W*) criteria, respectively; w_i denotes the weight of criterion i ; μ is the objective function value, defined as $\mu = \text{max}_k w'_k \mu_k$; and μ_k represents the consistency measure for expert k , defined by Eq. 7:

$$\mu_k = \text{max}_i \left\{ \left| \frac{w_B}{w_i} - a_{Bi}^k \right|, \left| \frac{w_i}{w_w} - a_{iW}^k \right| \right\} \quad (\text{Eq. 7})$$

where a_{Bi}^k denotes the preference of the best criterion *B* over criterion i , rated on a 1–9 scale by expert k , and a_{iW}^k denotes the preference of criterion i over the worst criterion *W*, rated on a 1–9 scale by expert k .

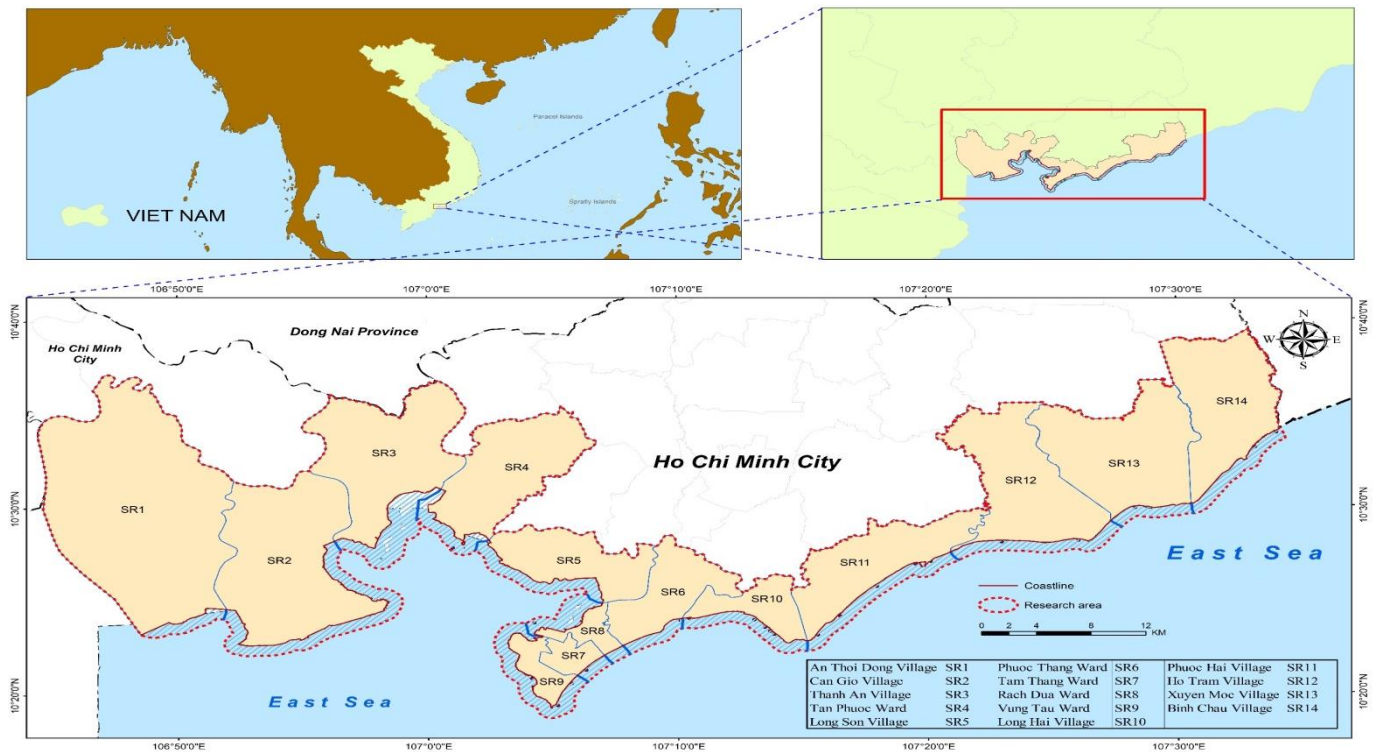


Figure 1 Geographical location of coastal communities in the coastal region of Ho Chi Minh City.

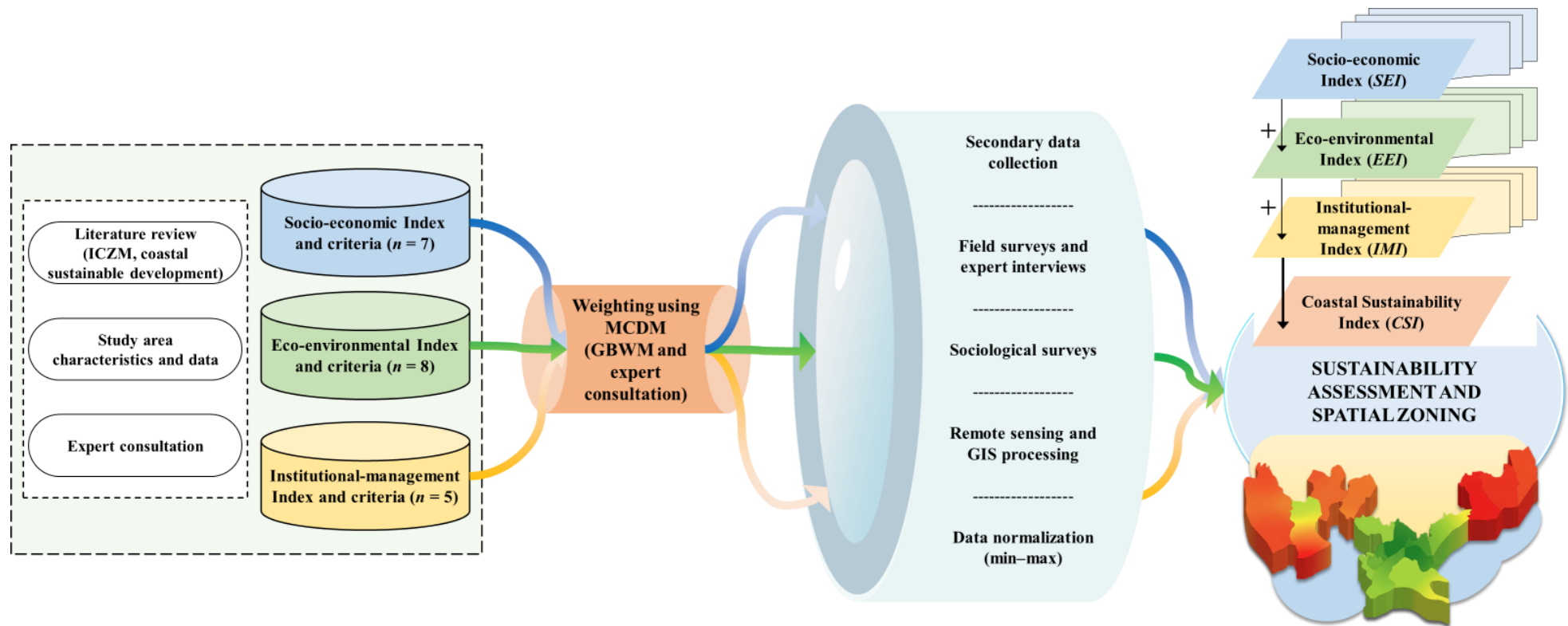


Figure 2 Methodology framework.

Table 1 Sustainability assessment criteria and their direction of influence

No.	Criteria	Notation	Unit	Description	Direction	Reference
Socioeconomic index						
1	Population density	SE_1	People km ⁻²	Population concentration per unit area, where higher values increase exposure and vulnerability	Negative (-)	Zuo et al. (2025)
2	Poverty rate	SE_2	%	Proportion of households below the poverty standard, where higher values indicate lower economic development	Negative (-)	Tan et al. (2023)
3	Income	SE_3	USD month ⁻¹	Average monthly income per capita, where higher values reflect stronger economic capacity and livelihood security	Positive (+)	Shah et al. (2025)
4	Unemployment rate	SE_4	%	Proportion of the labor force without employment, where higher values indicate lower labor market efficiency	Negative (-)	Mafi-Gholami et al. (2026)
5	Permanent housing rate	SE_5	%	Share of durable housing, where higher values indicate better living conditions and resilience	Positive (+)	Mafi-Gholami et al. (2026)
6	Education	SE_6	%	High school graduation rate, where higher values reflect better education access and human capital quality	Positive (+)	Schernewski et al. (2014)
7	Healthcare	SE_7	People	Number of healthcare personnel, where higher values indicate stronger healthcare capacity and resilience	Positive (+)	Schernewski et al. (2014)
Eco-environmental index						
1	Inundation area	EE_1	%	Proportion of area under regular inundation, where higher values indicate greater exposure	Negative (-)	Tran et al. (2025)
2	Coastal material	EE_2	–	Surface material of the coastal zone, with natural materials indicating higher resilience	Positive (+)	Cuong et al. (2023)
3	Shoreline change rate	EE_3	m year ⁻¹	Rate of shoreline movement over time, where higher values indicate greater instability	Negative (-)	Ahmadi et al. (2026)
4	Coastal forest coverage	EE_4	%	Proportion of coastal forest area, where higher values indicate stronger ecological protection	Positive (+)	Zhang et al. (2024b)
5	NH ₄ ⁺ concentration	EE_5	mg L ⁻¹	Ammonium concentration in water, where higher values indicate higher pollution levels	Negative (-)	Liu et al. (2025)
6	DO concentration	EE_6	mg L ⁻¹	Dissolved oxygen in water, where higher values indicate better water quality	Positive (+)	Mariscal-de-Souza et al. (2026)
7	PM10 concentration	EE_7	µg m ⁻³	Particulate matter (≤ 10 µm) concentration in air, where higher values indicate higher pollution	Negative (-)	Aryee et al. (2018)
8	SO ₂ concentration	EE_8	µg m ⁻³	Sulfur dioxide concentration in air, where higher values indicate higher pollution	Negative (-)	Fu et al. (2026)

Table 1 Sustainability assessment criteria and their direction of influence (*continued*)

No.	Criteria	Notation	Unit	Description	Direction	Reference
Institutional-management index						
1	Environmental communication	IM_1	–	Implementation of formal environmental communication programs, where higher values indicate stronger public awareness	Positive (+)	Kurniati et al. (2024)
2	Management personnel	IM_2	People	Number of environmental management personnel, where higher values indicate stronger capacity	Positive (+)	Kurniati et al. (2024)
3	Environmental violation	IM_3	Cases	Number of recorded environmental violations, where higher values indicate weaker compliance	Negative (–)	Tran et al. (2024)
4	Monitoring system	IM_4	Stations	Number of environmental monitoring stations, where higher values indicate stronger monitoring capacity	Positive (+)	Wan et al. (2024)
5	Environmental expenditure	IM_5	%	Share of budget for environmental protection, where higher values indicate stronger support	Positive (+)	Walling et al. (2024)

Consistency analysis was conducted to ensure the reliability of expert judgments and minimize potential bias in weight determination (Teng et al., 2025). The consistency ratio was calculated based on Eqs. 8–9 (Safarzadeh et al., 2018). The optimal weights and their deviation ranges were accepted when the aggregated consistency ratio (CR^G) was less than 0.1. The detailed results are presented in Figure 3. The error bars represent the deviation ranges, while the consistency ratios (CR^G) are shown for each subplot.

$$CR_k = w'_k \left(\frac{\mu_k}{CI^\theta} \right), \theta \text{ represents the sensitivity parameter } (\theta \geq 0), \forall k \in D \quad (\text{Eq. 8})$$

$$CR^G = \text{Max}_k(CR_k) \quad (\text{Eq. 9})$$

where CI^θ is the consistency index value, which is determined on the basis of Table 2.

2.2) Data collection and normalization

2.2.1) Dataset and sources

The dataset was compiled to ensure scientific validity and statistical robustness for quantitative analysis (Yu et al., 2010). Data for each criterion were collected from multiple sources (Table 3), including remote sensing and GIS-derived environmental data, secondary data from official reports, and primary data from field surveys, sociological surveys, and expert

interviews. This integrated approach enabled the development of a reliable spatial database, particularly given the limited availability of long-term data (AbdelRahman et al., 2023).

2.2.2) Data processing

In addition to secondary data, several criteria were derived through advanced data processing techniques (Table 3). The main procedures are described as follows:

- Inundation area (EE_1): Sentinel-1 SAR imagery (2025) representing dry and wet seasons was used. The data were preprocessed in the Sentinel Application Platform (SNAP), including orbit correction, thermal noise removal, radiometric calibration, speckle filtering, and terrain correction. Seasonal backscatter differences were analyzed to delineate inundation-prone areas using Eqs. 10–11 (Lu et al., 2004). The results were then integrated into ArcGIS 10.8 to quantify the proportion of inundated area for each subarea.

$$D = S_{wet} - S_{dry} \quad (\text{Eq. 10})$$

$$F(x) = \begin{cases} 1, & D < T \\ 0, & D \geq T \end{cases} \quad (\text{Eq. 11})$$

where D denotes the difference in backscatter between the wet and dry seasons; S_{wet} and S_{dry} are the corresponding backscatter values; T is the classification threshold, derived from histogram analysis; and $F(x)$ represents the binary classification output (1 for inundated areas and 0 for noninundated areas).

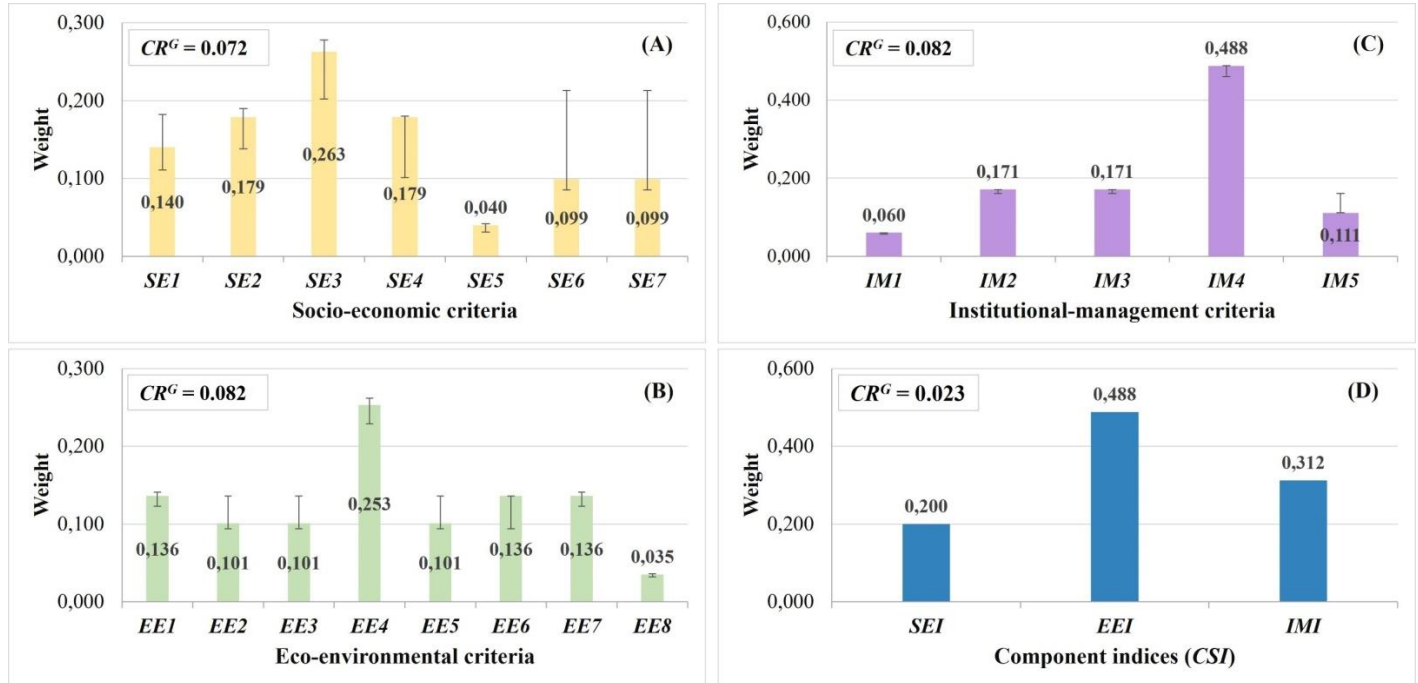


Figure 3 Optimal weights (W_i) and their deviation ranges ($W_i^{min} - W_i^{max}$) for (A) socioeconomic criteria, (B) eco-environmental criteria, (C) institutional-management criteria, and (D) component indices.

Table 2 The consistency index values of the GBWM

μ_k	1	2	3	4	5	6	7	8	9
CI^θ	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

- **Coastal material (EE_2):** Sentinel-2 imagery (2025) was used to classify typical coastal surface types, including built-up areas, artificial embankments, sandy beaches, wetlands, and rocky outcrops. The imagery was preprocessed using SNAP, ENVI 5.2, and ArcGIS 10.8. Supervised classification using the maximum likelihood classification (MLC) algorithm in ENVI 5.2 was performed on the basis of region of interest (ROI) samples and spectral signatures (Richards and Jia, 2022). Classification accuracy was assessed using 400 ground-truth samples (Israel, 1992), yielding a kappa coefficient of 0.87, indicating high reliability (Kraemer, 2015). The results were subsequently processed in ArcGIS 10.8 to extract the area of each coastal material type for each subarea.

- **Shoreline change rate (EE_3):** Multitemporal satellite imagery (Landsat 8 and Landsat 9) from 2015 to 2025, which was collected at 2-year intervals, was used. After preprocessing, normalization, and noise reduction, the shorelines at each time step were extracted using ENVI 5.2 and ArcGIS 10.8. A digital shoreline analysis system (DSAS) version 6.0 was subsequently used to calculate shoreline change rates using the linear regression rate (LRR), which captures long-term shoreline change trends (Fiawotoafor et al., 2005). The results enabled the classification of erosion ($LRR < 0$), accretion ($LRR > 0$), and stable conditions ($LRR \approx 0$) and were integrated into the GIS for subarea-level spatial analysis.

- **Coastal forest coverage (EE_4):** Landsat 9 imagery (2025) was analyzed using ENVI 5.2 and ArcGIS 10.8. Like EE_2 , a supervised MLC based on ROI samples was applied to distinguish coastal forests (including mangrove and nonmangrove types) from other land-cover classes, such as water, developed-up areas, and bare land [68]. The classification accuracy was validated using 400 ground-truth samples (Israel, 1992) (collected concurrently with EE_2), yielding a kappa coefficient of 0.95, indicating high reliability (Kraemer, 2015). The results were then aggregated in GIS to calculate the proportion of coastal forestland area relative to the total natural area for each subarea.

- **Environmental communication (IM_1):** Two respondent groups were surveyed: (1) 30 multisector policy-makers from the Department of Agriculture and Environment; the Department of Culture, Sports and Tourism; the Industrial Park and Export Processing Zone Management Board; and commune-level People's Committees; and (2) 74 representatives from the policy-receiving and compliance group, including coastal households and

business establishments (primarily in tourism and production) (Tran et al., 2025). The total sample size was 104, which was selected using stratified random sampling and met the minimum requirement for regional-scale studies ($N \geq 100$) to ensure representativeness and statistical validity (Sudman, 1976). Data were collected through structured questionnaires and face-to-face interviews and then compiled and analyzed quantitatively to construct a dataset for these criteria.

- **Remaining criteria:** Secondary data were collected from official statistical reports and subsequently verified and updated through in-depth interviews with local officials. The dataset was further calibrated using field survey results to ensure consistency with actual conditions.

2.2.3) Data normalization

Owing to differences in measurement units and scales, all the data were normalized using Eqs. 12–13 to ensure comparability across the criteria. Eq. 12 was applied to criteria with a positive relationship with sustainability, whereas Eq. 13 was used for criteria with a negative relationship (Table 1) (Adu et al., 2018). The normalized values were rescaled to a range of 0–1.

$$X_j = \frac{X_h - X_{min}}{X_{max} - X_{min}} \quad (\text{Eq. 12})$$

$$X_j = \frac{X_{max} - X_h}{X_{max} - X_{min}} \quad (\text{Eq. 13})$$

where X_j is the normalized value of the criterion; X_h is the observed value of the criterion; and X_{max} and X_{min} are the maximum and minimum observed values of the criterion, respectively.

2.3) Calculation, assessment, and mapping of coastal sustainability

On the basis of the criteria system and weights derived from the GBWM, the weighted linear combination method was applied to compute coastal sustainability indices (Poudel et al., 2026). The composite indices were constructed by integrating normalized criterion values with their corresponding weights using Eqs. 14–17, capturing both the magnitude and relative contribution of each component to overall sustainability.

Table 3 Data sources

No.	Criteria	Data type	Source	Reference
Socioeconomic index				
1	SE_1	Secondary statistical, commune-level, 2024	Statistical Yearbook	Ba Ria Vung Tau Statistical Office (2025), Ho Chi Minh City Statistical Office (2025)
2	SE_2	Secondary statistical and primary survey, 2024	Statistical Yearbook; field survey; in-depth interview	Ba Ria Vung Tau Statistical Office (2025), Ho Chi Minh City Statistical Office (2025)
3	SE_3	Secondary statistical and primary survey, 2024	Statistical Yearbook; field survey; in-depth interview	Ba Ria Vung Tau Statistical Office (2025), Ho Chi Minh City Statistical Office (2025)
4	SE_4	Secondary statistical, commune-level, 2024	Statistical Yearbook	Ba Ria Vung Tau Statistical Office (2025), Ho Chi Minh City Statistical Office (2025)
5	SE_5	Secondary statistical and primary survey, 2023	Statistical Yearbook; field survey; in-depth interview	Ba Ria Vung Tau Statistical Office (2024), Ho Chi Minh City Statistical Office (2024)
6	SE_6	Secondary statistical and primary survey, 2023	Statistical Yearbook; field survey; in-depth interview	Ba Ria Vung Tau Statistical Office (2024), Ho Chi Minh City Statistical Office (2024)
7	SE_7	Secondary statistical and primary survey, 2023	Statistical Yearbook; field survey; in-depth interview	Ba Ria Vung Tau Statistical Office (2024), Ho Chi Minh City Statistical Office (2024)
Eco-environmental index				
1	EE_1	Remote sensing (SAR), 10 m, 2025	Sentinel-1 GRD (IW mode, VV/VH polarization), Copernicus Data Space	–
2	EE_2	Remote sensing, 10 m, cloud cover < 10%, 2025	Sentinel-2 Level-2A, Copernicus Data Space	–
3	EE_3	Remote sensing, 30 m, cloud cover < 15%, 2015–2025	Landsat 8/9 OLI/TIRS Collection 2 Level-2, USGS EarthExplorer	–
4	EE_4	Remote sensing, 30 m, cloud cover < 10%, 2025	Landsat 9 OLI/TIRS Collection 2 Level-2, USGS EarthExplorer	–
5	EE_5	Secondary statistical, station-level, 2024	Environmental monitoring report	Department of Agriculture and Environment (2025)
6	EE_6	Secondary statistical, station-level, 2024	Environmental monitoring report	Department of Agriculture and Environment (2025)
7	EE_7	Secondary statistical, station-level, 2024	Environmental monitoring report	Department of Agriculture and Environment (2025)
8	EE_8	Secondary statistical, station-level, 2024	Environmental monitoring report	Department of Agriculture and Environment (2025)
Institutional-management index				
1	IM_1	Primary survey, 2025	Sociological surveys	–
2	IM_2	Primary survey, 2025	Field survey; in-depth interview	–
3	IM_3	Primary survey, 2025	Field survey; in-depth interview	–
4	IM_4	Secondary statistical and primary survey, 2024–2025	Environmental monitoring report; field survey; in-depth interview	Department of Agriculture and Environment (2025)
5	IM_5	Primary survey, 2025	Field survey; in-depth interview	–

$$SEI_j = \sum_i^7 SE_{ij} \times WSE_i \quad (\text{Eq. 14})$$

$$EEI_j = \sum_i^8 EE_{ij} \times WEE_i \quad (\text{Eq. 15})$$

$$IMI_j = \sum_i^5 IM_{ij} \times WIM_i \quad (\text{Eq. 16})$$

where SEI_j , EEI_j , and IMI_j denote the socioeconomic, eco-environmental, and institutional-management indices for spatial unit j , respectively; SE_{ij} , EE_{ij} , and IM_{ij} represent the normalized values of criterion i for spatial unit j ; and WSE_i , WEE_i , and WIM_i denote the weights of criterion i within each respective index.

$$CSI_j = SEI_j \times W_{SEI} + EEI_j \times W_{EEI} + IMI_j \times W_{IMI} \quad (\text{Eq. 17})$$

where CSI_j denotes the coastal sustainability index for spatial unit j and W_{SEI} , W_{EEI} , and W_{IMI} denote the weights of the socioeconomic, ecoenvironmental, and institutional management indices, respectively.

The resulting indices were spatially linked to corresponding units and mapped in ArcGIS 10.8. Using spatial overlay techniques, the data layers were integrated to generate continuous spatial distribution surfaces of coastal sustainability across the study area. The results were subsequently classified into four levels using the natural breaks (Jenks) method (low, moderate, high, and very high) to highlight spatial variations in sustainability among subareas (Bouchikhi et al., 2025).

Results and discussion

1) Spatial distribution of component indices

The results revealed pronounced spatial heterogeneity and complex interactions between natural conditions and development pressures across subareas (Figures 4–5). In terms of relative weight (Figure 3), the eco-environmental index was predominant (49%), followed by the institutional-management index (31%) and the socioeconomic index (20%). These findings highlight the foundational role of ecosystems in sustaining and shaping overall coastal sustainability (Lee et al., 2025).

Beyond the relative weighting of the three components, the GBWM results provided further insight into the internal structure of each dimension (Figure 3). Within the socioeconomic dimension, income (SE_3) received the highest weight (26%), reflecting its central role in shaping community resilience and adaptive capacity, whereas the permanent housing rate (SE_5)

carried the lowest weight (4%). In the eco-environmental dimension, coastal forest coverage (EE_4) was the most heavily weighted criterion (25%), which is consistent with its role in mitigating climate-related risks, whereas the SO_2 concentration (EE_8) contributed the least (4%). Within the institutional management dimension, environmental monitoring stations (IM_4) received a substantially higher weight (49%) than environmental communication stations did (IM_1 , 6%), reflecting the more actionable and measurable value of monitoring infrastructure relative to outreach activities. These weighting patterns were consistent with the characteristics of the study area, suggesting that the derived weights reflected meaningful differences in the relative importance of the criteria rather than statistical artifacts. Moreover, the aggregated consistency ratios remained below the recommended 0.1 threshold across all dimensions ($CR^G = 0.072$ – 0.082 for the criteria; 0.023 for the component indices), confirming the reliability and objectivity of the weighting process.

The socioeconomic index tended to be higher in areas with adequate levels of urbanization, industrialization, and infrastructure development (SR6, SR7, SR8, SR9, SR10, and SR11, respectively). In contrast, areas heavily reliant on traditional livelihoods and with limited social services (SR1, SR3, SR13, and SR14) had lower values. This pattern reflects disparities in development capacity and access to essential resources and indicates varying levels of vulnerability and sustainability under development pressure.

The eco-environmental index tended to be higher in subareas with extensive forest coverage and relatively stable ecosystems (e.g., SR1, SR3, SR12, SR13, and SR14), whereas areas under strong pressures from urbanization, shoreline change, and environmental degradation (SR4, SR7, SR8, SR9, and SR10) presented lower values. Subareas with low eco-environmental index values were often associated with higher shoreline change rates (> 1.8 m/year) or lower forest cover ($< 25\%$). In SR4, SR7, and SR8 in particular, rapid industrial and aquaculture expansion in recent years has accelerated mangrove loss and shoreline instability. In SR10, rapid urbanization occurred, but wastewater management was not well controlled, resulting in deteriorating coastal water quality. Together with sea-level rise, these pressures reduce ecosystem integrity and coastal resilience, explaining the low eco-environmental index values observed in these subareas. These results further reinforce the critical role of coastal ecosystems, particularly mangrove forests, in enhancing resilience to environmental risks and promoting coastal sustainability (Goldberg et al., 2020; Hassan et al., 2026; Lee et al., 2025).

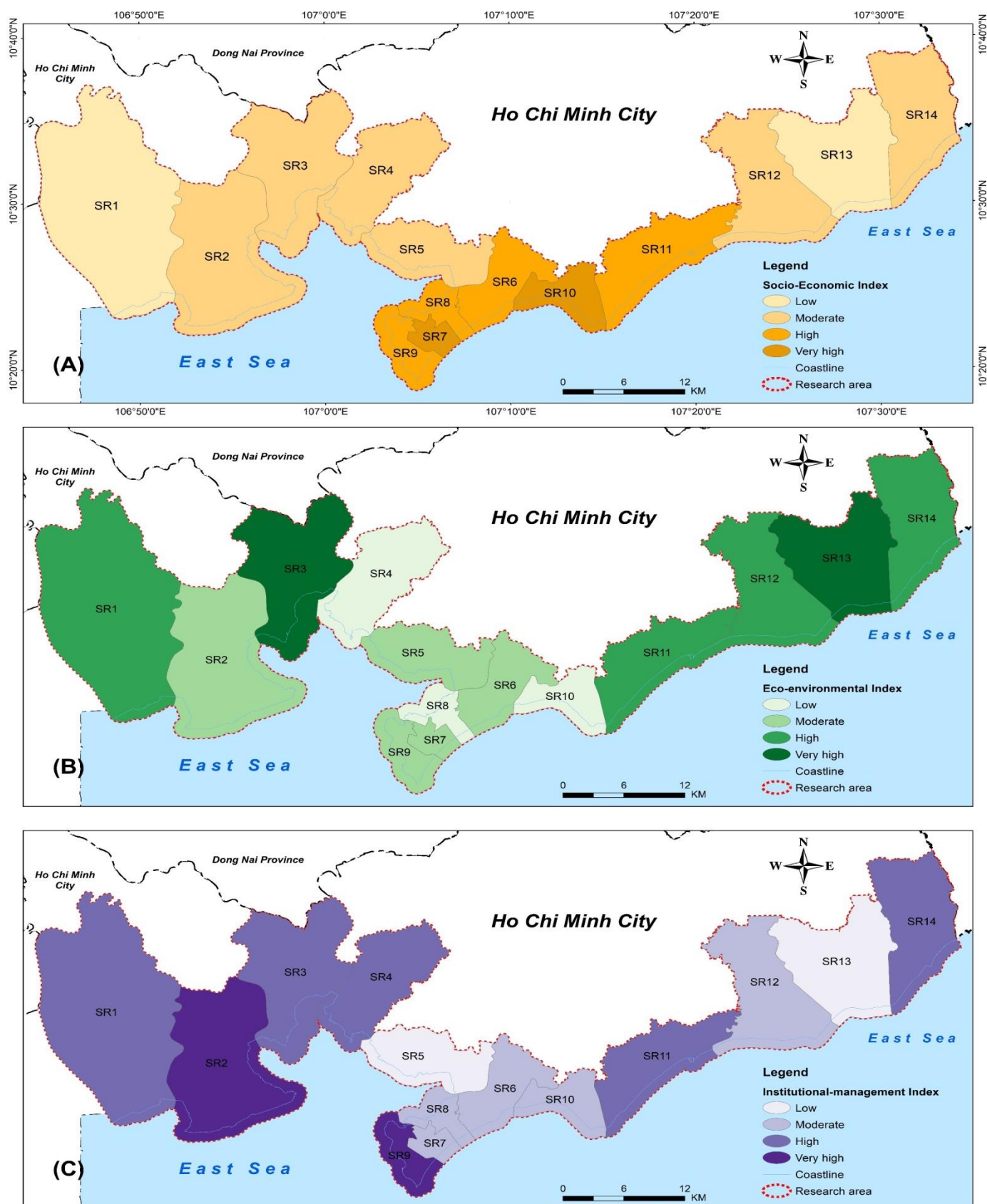


Figure 4 Spatial distribution of sustainability across component indices: (A) socioeconomic index, (B) eco-environmental index, and (C) institutional-management index.



Figure 5 Heatmap of weighted criteria contributions across study units.

The institutional-management index showed moderate variation across subareas, primarily reflecting differences in management capacity, monitoring systems, and environmental investment. Areas with more effective environmental monitoring and management (e.g., SR2, SR9, SR11, and SR14) presented higher values. Notably, criterion IM_4 played a predominant role in this dimension (49%), underscoring the importance of environmental monitoring in supporting decision-making and integrated coastal management. These findings reinforce the argument that institutional management functions as a coordinating mechanism within the ICZM framework rather than as an independent pillar (de Alencar et al., 2020; Fu et al., 2026; Zhang et al., 2024a).

2) Integrated coastal sustainability assessment

The composite sustainability index (CSI) revealed significant variation across subareas, ranging from 0.378 to 0.630 (Figures 6–7). Several subareas fell within low and moderate levels (07/14), reflecting relatively low sustainability and imbalances among components.

Subareas with high sustainability levels (SR2, SR3, SR9, SR11, and SR14) showed a relatively balanced distribution across the three dimensions, particularly through the combination of favorable environmental

conditions and effective management capacity. These areas demonstrate stronger adaptive capacity to climate change and socioeconomic development pressures. In contrast, subareas with low CSI values (SR4, SR5, SR6, and SR8) were affected by both environmental degradation and limited management capacity. These areas exhibit greater vulnerability to coastal risks, particularly inundation, erosion, and sea-level rise.

Notably, the presence of trade-offs among sustainable development components was observed. Several subareas (e.g., SR7, SR8, and SR10) presented relatively high socioeconomic indices but low eco-environmental values, indicating a contradiction between economic growth and coastal environmental protection (de Alencar et al., 2020; Mafi-Gholami et al., 2026). This pattern reflects rapid urbanization, industrial expansion, and aquaculture development at the expense of mangrove ecosystems and overall coastal environmental quality. These findings underscore the need for effective management mechanisms to balance short-term economic gains with environmental protection, thereby reducing pressure and ensuring long-term sustainability. Therefore, the application of ICZM approaches is necessary to meet development objectives and maintain a sustainable balance under increasing pressure.

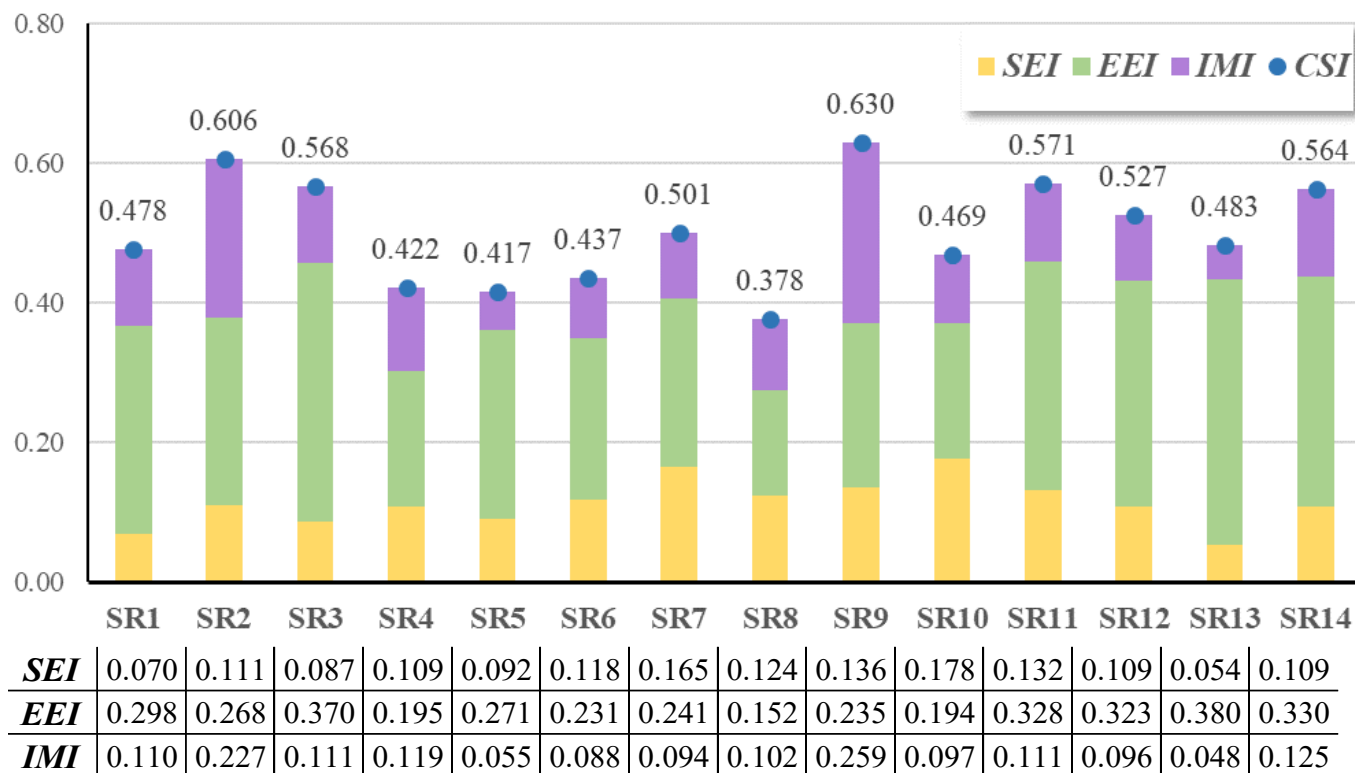


Figure 6 Contributions of the component indices to the composite sustainability index.

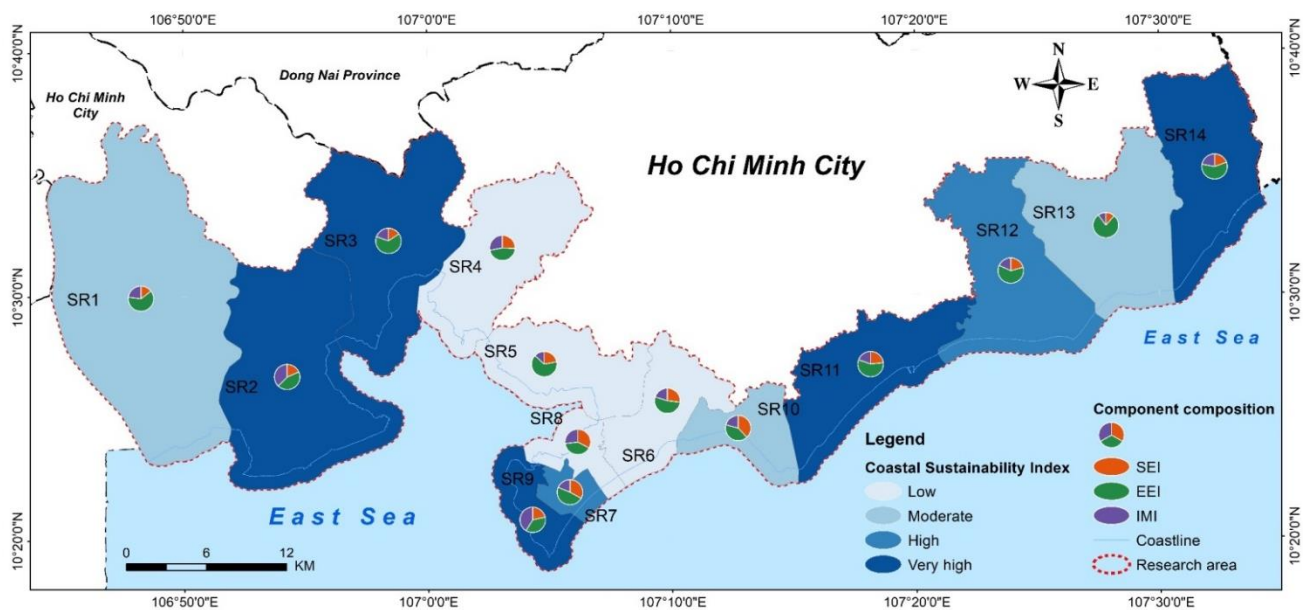


Figure 7 Spatial distribution of the coastal sustainability index.

3) Management implications and research limitations

The findings have several important implications for coastal management and sustainable development. First, the predominant role of the eco-environmental component highlights the need to prioritize the conservation and restoration of forest ecosystems as natural buffers against coastal hazards, particularly in subareas with low eco-environmental index values and high shoreline change rates (SR4 and SR7–SR10), while promoting nature-based solutions under increasing climate change pressure (Sieber et al., 2026). Second, for subareas exhibiting clear socioeconomic–environmental trade-offs (SR4, SR7, SR8, and SR10), the implementation of the ICZM should strengthen land use planning and environmental protection measures to better balance economic development with ecosystem protection. Third, the significant role of institutional management aspects underscores the need to strengthen governance capacity, particularly in environmental monitoring, resource allocation, and policy implementation. Improving management effectiveness can help reduce conflicts between economic development and environmental protection. This study further clarified the role of institutional management as a central coordinating mechanism rather than an independent pillar, thereby addressing the limitations identified in previous studies (Fu et al., 2026; Walling et al., 2024; Zhang et al., 2024a).

From a methodological perspective, integrating MCDM with GIS and remote sensing is effective for quantifying and spatially analyzing coastal sustainability while enhancing objectivity and practical applicability, particularly under data-limited conditions (AbdelRahman et al., 2023). The proposed framework also allows the flexible application of MCDM across different hazards or thematic domains, supporting context-specific assessments and diverse coastal management objectives (Tran et al., 2025).

The CSI shares the same objective as existing coastal sustainability indices by integrating multiple dimensions to support evidence-based decision-making (Ding and Tabeta, 2024; Mafi-Gholami et al., 2026; Wan et al., 2024; Wu et al., 2021; Zhao et al., 2025). However, it differs in the way these dimensions are conceptualized. Unlike four-pillar frameworks that treat institutional management as an independent dimension (de Alencar et al., 2020; Fu et al., 2026), the CSI positions institutional management as a coordinating mechanism that regulates interactions between the socioeconomic and eco-environmental dimensions, which is consistent with ICZM principles (Areizaga et al., 2012; Gallagher, 2010; Zhang et al., 2024a). This structure also reduces the conceptual redundancy and multicollinearity that may arise when management is treated as a standalone pillar (Greco et al., 2019; Nardo et al., 2005). Furthermore, compared with indices that

rely on extensive regional indicator systems (Mafi-Gholami et al., 2026) or focus primarily on the economy and ecology without spatial prioritization (Ding and Tabeta, 2024; Wu et al., 2021), the CSI uses more concise and spatially explicit criteria set by integrating remote-sensing-derived indicators with GIS-based mapping. This approach enables subarea-level prioritization, making the CSI particularly suitable for coastal contexts, where land–sea interactions are closely coupled, governance is fragmented across sectors, and management requires spatially explicit rather than aggregate evidence.

However, several limitations should be acknowledged. First, although improved by the GBWM, the weighting process still relies on expert judgment and may involve a degree of subjectivity. Second, the analysis was conducted at a single point in time and therefore does not capture temporal dynamics. Third, some criteria (e.g., environmental communication and management personnel) showed limited spatial differentiation, although they remain essential for reflecting implementation capacity. Fourth, the sample size for the sociological survey was relatively limited, which may affect the reliability of the criterion. Finally, the ICZM-based approach is primarily management oriented and does not fully capture broader governance dimensions.

Future research should expand toward integrating advanced quantitative methods (e.g., principal component analysis and machine learning) to enhance objectivity and scientific rigor. In addition, developing time series datasets would enable a transition from static assessment to dynamic analysis and forecasting. Furthermore, incorporating governance-related criteria (e.g., policy effectiveness, stakeholder participation, and transparency) would further strengthen the scientific robustness and practical applicability of the ICZM assessment framework.

Conclusions

In this study, an integrated ICZM-based framework was developed to quantify and map coastal sustainability in Ho Chi Minh City. Using three dimensions, socioeconomic (7 criteria), eco-environmental (8), and institutional-management (5), a composite sustainability index was constructed by integrating an MCDM (GBWM) with GIS and remote sensing and classified into four levels, namely, low, moderate, high, and very high. The results revealed that low-sustainability areas were associated with ecosystem degradation, high shoreline change rates ($> 1.8 \text{ m year}^{-1}$), low forest cover ($< 25\%$), and limited management and socioeconomic capacity. In contrast, higher-sustainability areas exhibited a more balanced integration of environmental conditions and management capacity. The eco-environmental dimension played a predominant role, highlighting the trade-offs between economic

development and environmental quality. From a policy perspective, the findings emphasize prioritizing ecosystem protection and restoration, particularly for mangrove forests, alongside controlling shoreline dynamics to enhance long-term coastal resilience and sustainability.

The ICZM-based approach, with a restructured criteria system that strengthens linkages among components and clarifies the coordinating role of institutional management, proves effective for integrated sustainability assessment and spatial prioritization in multihazard contexts. The results provide a quantitative basis for identifying priority intervention areas and supporting more targeted coastal management. More fundamentally, the proposed CSI goes beyond site-specific evaluation by providing a transferable ICZM-based framework for spatially explicit sustainability assessment across coastal regions. However, the criteria system should be adapted to local conditions, given variations in socioeconomic, eco-environmental, and governance contexts.

This study is subject to several limitations, including its reliance on data from a single time point, which does not fully capture temporal dynamics and climate change scenarios. In addition, the selection and normalization of criteria may still involve some subjectivity. Future research should integrate time series analysis, scenario simulation, and dynamic modeling to improve the predictive capacity and support more effective decision-making in coastal management.

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Data availability statement

Information and data used in the study will be disclosed upon request.

Author ORCID

Thanh-Minh Tran: 0009-0006-5544-5252

Thi-Diem-Loan Tran: 0009-0000-1899-8575

Minh-Luan Nguyen: 0009-0003-6136-4713

Tan-Cuong Le: 0009-0001-4292-3159

Author contributions

Thanh-Minh Tran: Conceptualization, Methodology, Formal analysis, Data curation, Writing – Original draft, Writing – Review & editing, Project administration, Funding acquisition

Thi-Diem-Loan Tran: Methodology, Software, Validation, Investigation, Resources, Writing – Review & editing, Visualization

Minh-Luan Nguyen: Software, Validation, Formal analysis, Investigation, Resources, Visualization

Tan-Cuong Le: Conceptualization, Methodology, Resources, Data curation, Writing – Original draft, Writing – Review & editing, Supervision, Project administration, Funding acquisition

Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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