

EVALUATION OF MARINE ECOLOGICAL CARRYING CAPACITY IN JIAXING CITY, CHINA

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Abstract. Marine Ecological Carrying Capacity (MECC) is a key indicator for the sustainable development of coastal areas. Based on the Pressure-State-Response (PSR) framework, this study proposes a conceptual model of MECC and constructs a set of MECC evaluation index systems tailored to the marine characteristics of Jiaxing City, China. The entropy weight method is used to determine the weights of each indicator, and the TOPSIS model is used to quantitatively calculate the interannual changes in MECC. The evaluation results show that from 2018 to 2023, the MECC of Jiaxing showed a year-by-year upward trend, increasing from 0.3823 in 2018 to 0.5801 in 2023. The key driving forces were the establishment of marine protected areas, the improvement of urban sewage treatment efficiency, and the enhancement of scientific research and technological support capabilities. These measures have significantly reduced the pressure of human socio-economic activities on the marine resource environment, strengthening protection of marine ecology and promoting sustainable development of Jiaxing. The case study of Jiaxing indicates that in coastal management, implementing protective policies, promoting environmental governance, and continuously investing in technological innovation are keyways for improving MECC.

Keyword: *ecological carrying capacity, marine ecological protection, TOPSIS model, evaluation index system*

Introduction

With the acceleration of global industrialization and urbanization, the demand and dependence of human society on marine resources are deepening increasingly (Mastrantonis and Dubininkas, 2022; Pena et al., 2024). Marine economic activities have become unprecedentedly active and a new growth engine for the global economy (Santos et al., 2024). However, the increasingly tension relationship between high-intensity development activities and relatively fragile marine ecosystem has led to widespread global issues such as coastal environmental pollution, declining biodiversity, and ecosystem degradation (Gotama et al., 2024). Jiaxing is located on the southern wing of the Yangtze River Delta and the northern bank of Hangzhou Bay (Zhang et al., 2014). Its unique geographical location endows it with special characteristics and significance for its marine economy and ecological environment. Jiaxing Port is an important hub for river-sea transportation in the Yangtze River Delta, with rapid development of port shipping (Wu and Zhang, 2018). At the same time, its coastal areas are also an important offshore wind power base (Zhu et al., 2021). Although these high-intensity marine industrial activities have created enormous economic value, they also brought significant environmental pressure on relatively fragile marine ecosystems (Ogara et al., 2025; Kumar et al., 2020; Willaert et al., 2019).

Existing studies have shown that the marine areas of Jiaxing are facing a series of severe ecological and environmental challenges such as composite pollution sources and ecosystem degradation (Xu et al., 2015). Therefore, it is urgent to study Marine Ecological Carrying Capacity (MECC) in this region to guide human development activities and ensure the sustainable development of the ocean. To date, various evaluation frameworks and methods, including the System Dynamics (SD) model, Pressure-State-Response (PSR) model, and Driving Force-Pressure-State-Impact-Response (DPSIR) model (Rashidian et al., 2025; Sahana et al., 2022; Faseyi et al., 2023), have been proposed to study MECC. These studies have provided important theoretical support and methodological references for understanding the complex interaction between human activities and the marine environment. Although there have been numerous practices of MECC in Ningbo, Zhejiang Province, and even the entire Yangtze River Delta (Ying et al., 2022; He et al., 2021), systematic research results on the MECC of Jiaxing have not yet been formed. Existing studies mainly focus on regional assessments or analyses of specific pollutants (Wang et al., 2021; Keita et al., 2009), lacking a scientific framework that can comprehensively reflect the overall MECC status of the marine ecosystem in Jiaxing.

Based on the Pressure-State-Response (PSR) framework, a conceptual model of MECC is proposed. Then a scientific and reasonable evaluation index system is established taking into account Jiaxing's socio-economic development level, resource and environmental endowments, and marine natural ecological conditions. A quantitative analysis of the dynamic changes in Jiaxing's MECC from 2018 to 2023 was conducted using the Entropy Weight-TOPSIS model. It expands the methods for MECC evaluation and provides an empirical reference for MECC research in similar coastal cities.

Materials and methods

Study area

Jiaxing (*Fig. 1*) is located in the northeastern part of Zhejiang Province, eastern China, within the core area of the Hangzhou-Jiaxing-Huzhou Plain. It borders the Hangzhou Bay to the east, the Qiantang River to the south, the Taihu Lake to the north, and the Tianmu River system to the west (Zhang et al., 2022). As a typical river-sea intersection area, it has been designated as a national coastal economic opening area in China. The city has a land area of 4237 km², a marine area of 1559 km², and a coastline length of 81.84 km (Zhang et al., 2014). This geographical location gives it a composite ecosystem that includes estuarine wetlands, intertidal zones, and uninhabited islands, making it an important part of the ecological barrier in the Yangtze River Estuary-Hangzhou Bay (Xu et al., 2024).

Conceptual model

Di Qianbin believes that the carrying capacity of the ocean reflects the interactive coupling relationship between the “ocean” (as the material basis) and the “human” (as the carried subjects) in the marine human-land system (Di and Han, 2005). The “Pressure-State-Response” (PSR) model is an evaluation framework used to analyze the relationship between the environment and human activities (Sadeghi et al., 2023). Based on the PSR framework, a conceptual model of MECC is proposed. The advantage of this model lies in its ability to effectively reflect the interactive relationship between

humans and the ocean, providing theoretical support for the subsequent construction of evaluation indicators.

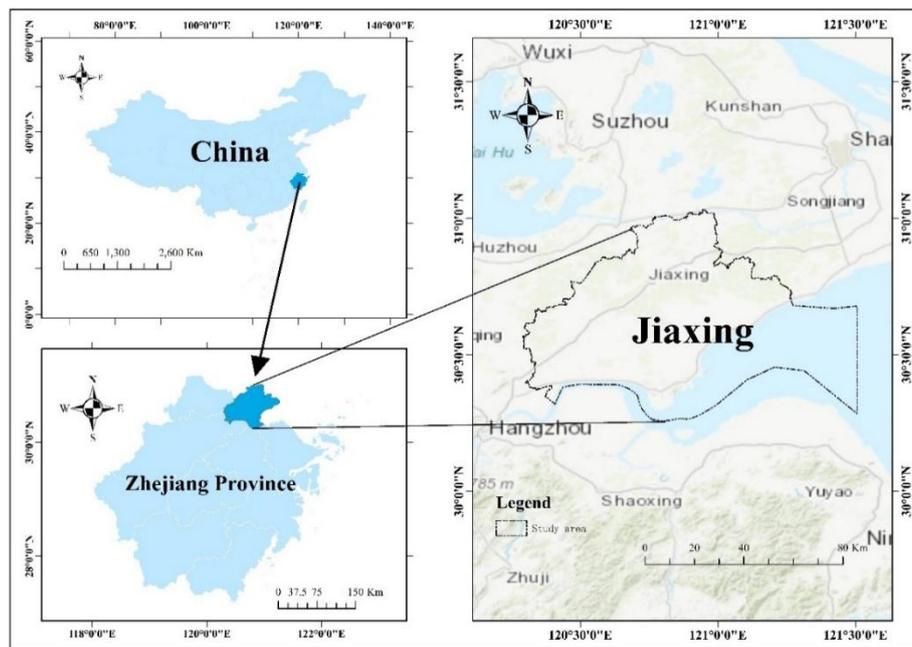


Figure 1. Location of the study area of Jiaxing City

In this conceptual model (Fig. 2), the carrier refers to the marine ecosystem, which includes resource supply capacity and environmental pollution absorption capacity. The resource supply capacity covers the resources provided by the ocean, including marine areas, tidal flats, and tourism resources; the environmental pollution absorption capacity refers to the environment's ability to purify pollutants and maintain biodiversity. The carried objects are human socio-economic activities, including various behaviors of development, utilization and protection.

In the interactive relationship between “carrier and carried objects”, the resources and environment of the carrier represent the “state”, and the activities of the carried objects include “pressure” and “response”. The “state” refers to the supporting capacity of the carrier (marine ecosystem). On the one hand, as the material basis, the carrier provides resource support for the development of the carried objects (such as tourism, port, and fishery activities); on the other hand, it exerts its ability to absorb environmental pollution absorption to adapt to the pollution emissions of carried objects (such as wastewater and energy consumption) and maintain ecological balance. The “pressure” refers to the over-exploitation behaviors of the carried objects, and the “response” refers to the protective behaviors between the carried objects. The “resource and environment” state of the carrier determines the scale of “pressure-type activities” that can be supported and the effectiveness of “response-type activities”. If “pressure-type activities” (such as overfishing and sewage discharge) exceed the threshold of the carrier, the supporting capacity of the carrier will be weakened. “Response-type activities” (such as stock enhancement, establishment of protected areas, and sewage treatment) can increase the threshold of the carrier, thereby effectively expanding the MECC boundary. Ultimately,

MECC is a dynamic equilibrium state formed by the joint action of the “innate endowment of the carrier” and the “acquired regulation of the carried objects”.

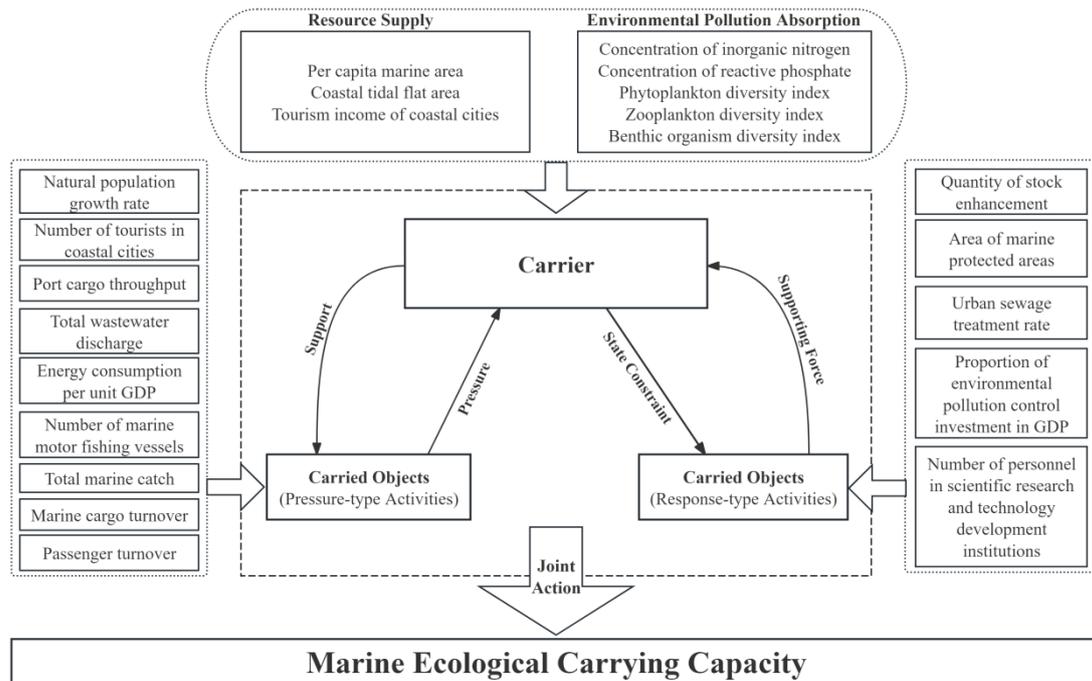


Figure 2. Conceptual model of MECC

Evaluation index framework

The MECC evaluation index framework of Jiaxing (Table 1) consists of four levels: Target Layer, Criterion Layer, Element Layer, and Indicator Layer. The Target Layer is the MECC of Jiaxing; the Criterion Layer includes two core perspectives: Carried Objects and Carrier; the Element Layer is a further refinement of the Criterion Layer, including Human Socio-Economic Activities (under Carried Objects) and Resource Supply Capacity and Environmental Pollution Absorption Capacity (under Carrier); the Indicator Layer consists of 22 indicators. The MECC evaluation index framework integrates “resources, environment, and human activities” and covers the dual perspectives of “carrier-carried objects”, avoiding the limitations of single-dimensional evaluation. It highlights the regional characteristics of Jiaxing (such as tidal flats, ports, and tourism) and systematically incorporates the indicators (such as “ecological restoration and pollution control”) to reflect the active regulation of humans on marine ecology. This is in line with the concept of sustainable development.

Data sources

The indicator data for the MECC evaluation of Jiaxing from 2018 to 2023 were obtained from the Statistical Yearbook of Natural Resources and Environment of Zhejiang Province, Statistical Yearbook of Jiaxing, Statistical Communique on National Economic and Social Development of Jiaxing, Communique on the Ecological Environment of Jiaxing, and Communique on Marine Environmental Quality of Jiaxing. The details are shown in Table 2.

Table 1. MECC evaluation index framework of Jiaxing

Target layer	Criterion layer	Element layer	Indicator layer	Unit	Indicator attribute
Marine ecological carrying capacity	Carried objects	(HI) Human socio-economic activities	(H1) Natural population growth rate	‰	-
			(H2) Number of tourists in coastal cities	10 ⁴ person-times	-
			(H3) Port cargo throughput	10 ⁴ tons	-
			(H4) Total wastewater discharge	10 ⁴ tons	-
			(H5) Energy consumption per unit GDP	tce/10 ⁴ CNY	-
			(H6) Number of marine motor fishing vessels	Vessel	-
			(H7) Total marine catch	ton	-
			(H8) Marine cargo turnover	10 ⁴ ton/km	-
			(H9) Passenger turnover	10 ⁴ person/km	-
			(H10) Quantity of stock enhancement	10 ⁴ individuals	+
			(H11) Area of marine protected areas	km ²	+
			(H12) Urban sewage treatment rate	%	+
			(H13) Proportion of environmental pollution control investment in GDP	%	+
			(H14) Number of personnel in scientific research and technology development institutions	Person	+
	Carrier	(RI) Resource supply capacity	(R1) Per capita marine area	m ² /person	+
			(R2) Coastal tidal flat area	10 ⁴ mu	+
			(R3) Tourism income of coastal cities	10 ⁸ CNY	+
		(EI) Environmental pollution absorption capacity	(E1) Concentration of inorganic nitrogen	mg/L	-
			(E2) Concentration of reactive phosphate	mg/L	-
			(E3) Phytoplankton diversity index	/	+
			(E4) Zooplankton diversity index	/	+
			(E5) Benthic organism diversity index	/	+

“+” indicates positive indicators, and “-” indicates negative indicators

Table 2. Original data of evaluation indicators for Jiaxing MECC

Indicator	2018	2019	2020	2021	2022	2023	Unit
(H1) Natural population growth rate	1.75	1.86	0.43	-0.73	-1.35	-3.46	‰
(H2) Number of tourists in coastal cities	2040	2281	1878	609	533	844	10 ⁴ person-times
(H3) Port cargo throughput	9689.4	10913.05	11714.54	12690.8	13240.48	13960.43	10 ⁴ tons
(H4) Total wastewater discharge	41392.18	42364.28	43408.51	46174.86	44493.98	42978.95	10 ⁴ tons
(H5) Energy consumption per unit GDP	0.457	0.435	0.43	0.438	0.44	0.417	tce/10 ⁴ CNY
(H6) Number of marine motor fishing vessels	322	310	302	157	162	161	Vessel
(H7) Total marine catch	589	558	523	526	521	521	ton
(H8) Marine cargo turnover	441404	454887	622761	830228	1113865	698845	10 ⁴ ton/km
(H9) Passenger turnover	212948	216951	81872	81072	48440	89680	10 ⁴ person/km
(H10) Quantity of stock enhancement	10029.24	13393.33	12900	9573.6	10542	11201	10 ⁴ individuals
(H11) Area of marine protected areas	0	0	0	118	118	118	km ²
(H12) Urban sewage treatment rate	94.36	97.49	98.42	98.60	99.01	99.30	%
(H13) Proportion of environmental pollution control investment in GDP	1.22	1.14	1.85	1.35	1.11	0.95	%
(H14) Number of personnel in scientific research and technology development institutions	134	125	211	544	853	899	Person
(R1) Per capita marine area	318	282	278	273	271	269	m ² /person
(R2) Coastal tidal flat area	4.73*	4.83	4.82	4.71	4.68	4.65	10 ⁴ mu
(R3) Tourism income of coastal cities	206.38	244.47	197.16	96.26	73.41	95.79	10 ⁸ CNY
(E1) Concentration of inorganic nitrogen	1.226	1.911	1.106	1.561	1.869	1.535*	mg/L
(E2) Concentration of reactive phosphate	0.063	0.052	0.047	0.064	0.063	0.058*	mg/L
(E3) Phytoplankton diversity index	2.03	1.32	2.91	1.91	2.64	2.16*	/
(E4) Zooplankton diversity index	1.63	1.37	1.12	2.57	2.45	1.83*	/
(E5) Benthic organism diversity index	0.91	0	0.16	0.1	0.13	0.26*	/

The coastal tidal flat area (R2) in 2018 is the average value of 2019-2023; the concentrations of inorganic nitrogen (E1), reactive phosphate (E2), phytoplankton diversity index (E3), zooplankton diversity index (E4), and benthic organism diversity index (E5) in 2023 are the average values of 2018-2022

Calculation methods

Indicator standardization

Indicators can be divided into “positive” and “negative” indicators according to their attributes, usually denoted by “+” and “-” (Ma et al., 2017). For positive indicators, larger values have a positive impact on the results, and the opposite is true for negative indicators (Table 1). Due to different dimensions of indicator values, raw data cannot be directly compared or calculated. Therefore, it is necessary to standardize the indicators according to their different attributes (Khani et al., 2025). The range of the standardized values is between 0 and 1.

For positive indicators:

$$Y_{ij} = \frac{(X_{ij} - X_{imin})}{(X_{imax} - X_{imin})} \quad (\text{Eq.1})$$

For negative indicators:

$$Y_{ij} = \frac{(X_{imax} - X_{ij})}{(X_{imax} - X_{imin})} \quad (\text{Eq.2})$$

where, X_{ij} is the raw data; Y_{ij} is the standardized value of X_{ij} ; X_{imax} and X_{imin} are the maximum and minimum values of the indicator X_{ij} respectively.

Determination of indicator weights

The entropy weight method is used to determine the weights of indicators. The entropy weight method is an objective weighting method that judges the utility value of indicators based on the degree of variation in the evaluation indicators (Cunha-Zeri et al., 2022). The weights are determined by calculating the entropy value of each indicator, and the specific calculation steps are as follows:

(1) Establish the original data matrix. Assuming there are m evaluation indicators and n evaluation objects (years); the original data matrix is $X = (x_{ij})_{m \times n}$, where, x_{ij} represents the value of the i -th evaluation indicator in the j -th evaluation object.

(2) Construct the normalized matrix. The original data matrix is standardized using Equations 1 and 2 to obtain the normalized matrix $Y = (y_{ij})_{m \times n}$, where, y_{ij} represents the standardized value of the i -th evaluation indicator in the j -th evaluation object.

(3) Calculate the proportion of evaluation indicators as follows:

$$F_{ij} = \frac{(1 + y_{ij})}{\sum_{j=1}^n (1 + y_{ij})} \quad (\text{Eq.3})$$

where, F_{ij} represents the proportion of the standardized value of the i -th evaluation indicator to the total standardized value of that indicator.

(4) Calculate the entropy value as follows:

$$E_i = -K \sum_{j=1}^n F_{ij} \ln F_{ij} \quad (\text{Eq.4})$$

where, E_i represents the entropy value of the i -th evaluation indicator; K is a constant, and $K = \frac{1}{\ln n}$.

(5) Calculate the weight as follows:

$$W_i = \frac{1 - E_i}{\sum_{i=1}^m (1 - E_i)} \quad (\text{Eq.5})$$

where, w_i is the weight of the i -th indicator, $W_i \in [0, 1]$, $\sum_{i=1}^m W_i = 1$.

TOPSIS model

This study uses the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to comprehensively evaluate the Marine Ecological Carrying Capacity (MECC) of Jiaxing, aiming to quantify its dynamic change characteristics from 2018 to 2023. As a classic comprehensive evaluation method for multi-criteria decision analysis, the TOPSIS model has the advantages of authenticity, intuitiveness, and reliability in the overall evaluation process. This makes it suitable for comparison and optimization of multiple indicators and schemes (Lü et al., 2021). Its basic principle is to determine the

proximity of each evaluation object to the ideal state by calculating the Euclidean distances between the evaluation object and the positive/negative ideal solutions, so as to judge the superiority of the evaluation results based on this proximity (Atenidegbe and Mogaji, 2023). The specific calculation steps are as follows:

(1) Construction of standardized evaluation matrix

The standardized decision matrix Y is obtained by calculating the raw indicator data using *Equations 1* and *2*:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \vdots & y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \quad (\text{Eq.6})$$

(2) Evaluation matrix weighting based on entropy weight

The standardized evaluation matrix Y is multiplied by the indicator weights W_i obtained from the entropy weight method to obtain the weighted standardized evaluation matrix U :

$$U = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1n} \\ u_{21} & u_{22} & \cdots & u_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ u_{m1} & u_{m2} & \cdots & u_{mn} \end{bmatrix} = \begin{bmatrix} y_{11} \times W_1 & y_{12} \times W_1 & \cdots & y_{1n} \times W_1 \\ y_{21} \times W_2 & y_{22} \times W_2 & \cdots & y_{2n} \times W_2 \\ \vdots & \vdots & \vdots & \vdots \\ y_{m1} \times W_i & y_{m2} \times W_i & \vdots & y_{mn} \times W_i \end{bmatrix} \quad (\text{Eq.7})$$

(3) Determination of positive and negative ideal solutions

Let the positive ideal solution U^+ be composed of the maximum values of the i -th evaluation indicator of the j -th evaluation objects, and the negative ideal solution U^- be composed of the minimum values of the i -th evaluation indicator among the j -th evaluation objects:

$$U^+ = \{ \max u_{ij} | i=1,2,\dots,m \} = \{ u_1^+, u_2^+, \dots, u_m^+ \} \quad (\text{Eq.8})$$

$$U^- = \{ \min u_{ij} | i=1,2,\dots,m \} = \{ u_1^-, u_2^-, \dots, u_m^- \} \quad (\text{Eq.9})$$

(4) Distance calculation

Let D_j^+ be the Euclidean distance between the j -th evaluation object and the positive ideal solution, and D_j^- be the Euclidean distance between the j -th evaluation object and the negative ideal solution:

$$D_j^+ = \sqrt{\sum_i^m (u_i^+ - u_{ij})^2} \quad (\text{Eq.10})$$

$$D_j^- = \sqrt{\sum_i^m (u_i^- - u_{ij})^2} \quad (\text{Eq.11})$$

(5) Calculation of closeness

Let T_j represent the closeness of the evaluation object to the ideal solution, $T_j \in [0,1]$:

$$T_j = \frac{D_j^-}{D_j^+ + D_j^-} \quad (\text{Eq. 12})$$

In this study, the quantitative value of MECC is directly defined by the core output of the TOPSIS model, which is the closeness degree T_j (Eq. 12). Specifically, the numerical value of T_j intuitively reflects the relative level of MECC in a specific evaluation year, $T_j \in [0, 1]$. The closer T_j is to 1, the closer the MECC is to the optimal state. To analyze the internal structural characteristics of MECC and determine its driving mechanisms, three subsystem indices are established, with specific connotations defined as follows: Human Socio-Economic Activity Index (HI): Quantifies the intensity and scale of human behaviors related to the marine ecosystem, including the development, utilization, and protection of marine resources and the marine environment; Resource Supply Capacity Index (RI): Characterizes the ability of the marine ecosystem to provide available resources, including key components such as marine space, tidal flats, and coastal tourism resources that support socio-economic development; Environmental Pollution Absorption Capacity Index (EI): Reflects the self-purification potential of the marine environment for pollutants and its capacity to maintain biodiversity, which is the core ecological basis for sustaining MECC.

HI, RI and EI share the same calculation framework as MECC and are all derived using the TOPSIS model. The input data for these three indices are the underlying indicators of each subsystem (Table 1). The closeness degrees obtained by each subsystem are respectively designated as HI, RI, and EI, which collectively provide a multi-dimensional perspective to interpret the internal structure of MECC. Based on the multi-level results of the overall carrying capacity, subsystem indices, and underlying specific indicator indices, the evolution process, structural features, and main influencing factors of Jiaxing's MECC is revealed, providing a detailed data support for subsequent cause analysis and policy recommendations.

Results and analysis

The results of indicator standardization and indicator weights

Table 3 presents the results of indicator standardization and indicator weights. The weight allocation and specific indicators of each subsystem are different, resulting in different degrees of impact on the marine ecological carrying capacity.

In the subsystem of human socio-economic activities, the area of marine protected areas (H11) is the core influencing factor with a weight of 0.0812. In contrast, the weight of energy consumption per unit of GDP (H5) is the lowest, only 0.0286. For the resource supply subsystem, the weight distribution of indicators is relatively uniform. In these indicators, the weight of the tourism revenue of coastal cities (R3) is the highest, reaching 0.0500, and that of the per capita marine area (R1) and coastal tidal flat area (R2) is relatively low, at 0.0471 and 0.0452 respectively. In the subsystem of environmental pollution assimilation, the concentrations of inorganic nitrogen (E1) and reactive phosphate (E2) play a dominant role in carrying capacity, with the weights of 0.0460 and 0.0521 respectively. In contrast, the weights of phytoplankton (E3), zooplankton (E4), and benthic biodiversity index (E5) are relatively low, at 0.0327, 0.0432, and 0.0427 in sequence.

Table 3. Indicator standardization and indicator weights

Indicator	2018	2019	2020	2021	2022	2023	Index weight
(H1) Natural population growth rate	0.0207	0.0000	0.2688	0.4868	0.6034	1.0000	0.0439
(H2) Number of tourists in coastal cities	0.1379	0.0000	0.2305	0.9565	1.0000	0.8221	0.0530
(H3) Port cargo throughput	1.0000	0.7135	0.5258	0.2973	0.1686	0.0000	0.0385
(H4) Total wastewater discharge	1.0000	0.7967	0.5784	0.0000	0.3515	0.6682	0.0317
(H5) Energy consumption per unit GDP	0.0000	0.5500	0.6750	0.4750	0.4250	1.0000	0.0286
(H6) Number of marine motor fishing vessels	0.0000	0.0727	0.1212	1.0000	0.9697	0.9758	0.0666
(H7) Total marine catch	0.0000	0.4559	0.9706	0.9265	1.0000	1.0000	0.0376
(H8) Marine cargo turnover	1.0000	0.9799	0.7303	0.4218	0.0000	0.6172	0.0342
(H9) Passenger turnover	0.0238	0.0000	0.8016	0.8064	1.0000	0.7553	0.0497
(H10) Quantity of stock enhancement	0.1193	1.0000	0.8708	0.0000	0.2535	0.4261	0.0467
(H11) Area of marine protected areas	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	0.0812
(H12) Urban sewage treatment rate	0.0000	0.6336	0.8219	0.8583	0.9413	1.0000	0.0312
(H13) Proportion of environmental pollution control investment in GDP	0.3000	0.2111	1.0000	0.4444	0.1778	0.0000	0.0369
(H14) Number of personnel in scientific research and technology development institutions	0.0116	0.0000	0.1111	0.5413	0.9406	1.0000	0.0610
(R1) Per capita marine area	1.0000	0.2653	0.1837	0.0816	0.0408	0.0000	0.0471
(R2) Coastal tidal flat area	0.4444	1.0000	0.9444	0.3333	0.1667	0.0000	0.0452
(R3) Tourism income of coastal cities	0.7773	1.0000	0.7234	0.1336	0.0000	0.1308	0.0500
(E1) Concentration of inorganic nitrogen	0.8509	0.0000	1.0000	0.4348	0.0522	0.4671	0.0460
(E2) Concentration of reactive phosphate	0.0588	0.7059	1.0000	0.0000	0.0588	0.3529	0.0521
(E3) Phytoplankton diversity index	0.4465	0.0000	1.0000	0.3711	0.8302	0.5283	0.0327
(E4) Zooplankton diversity index	0.3517	0.1724	0.0000	1.0000	0.9172	0.4897	0.0432
(E5) Benthic organism diversity index	1.0000	0.0000	0.1758	0.1099	0.1429	0.2857	0.0427

MECC evaluation results

As shown in *Figure 3*, the MECC increased year by year, which is consistent with the overall trend of strengthened ecological protection in coastal cities of the Yangtze River Delta (Yu and Zhao, 2022; Zhu and Sun, 2023). The MECC index increased from 0.3823 in 2018 to 0.5801 in 2023, with an average annual growth rate of 8.7%. However, affected by each subsystem and the external disturbance of the COVID-19 pandemic, the MECC showed phased changes.

From 2018 to 2019, although the human socio-economic activity index increased, due to the dual negative effects of resource supply and environmental pollution absorption

capacity, the final MECC only fluctuated slightly, increasing from 0.3823 to 0.3826. From 2019 to 2021, in the main period affected by COVID-19, the MECC still grew rapidly although a significant decline in resource supply capacity: the pandemic-induced adjustments to social and economic activities (such as restricting travel and reducing marine development intensity) alleviated the pressure on the marine ecosystem; local ecological protection policies optimized in pandemic prevention enhanced the environmental pollution absorption capacity. This dual mechanism, coupled with the stabilization of core economic indicators, worked in synergy to drive the growth of MECC. From 2021 to 2023, as the socio-economic order gradually recovered, the weakening of the short-term environmental improvement effect of the epidemic, as well as the continuous decline in resource supply capacity, offset the driving force of human socio-economic activities. This results in a slowdown in the growth rate of MECC, increasing from 0.5387 to 0.5801.

Therefore, the growth of the human socio-economic activity index has effectively promoted the improvement of MECC. The continuous deterioration of resource supply capacity has become a key bottleneck restricting the improvement of MECC. At the same time, as a major external event, COVID-19 has shaped the periodic changes of MECC by regulating the interaction between human activities, environmental capacity and resource supply in 2019-2021.

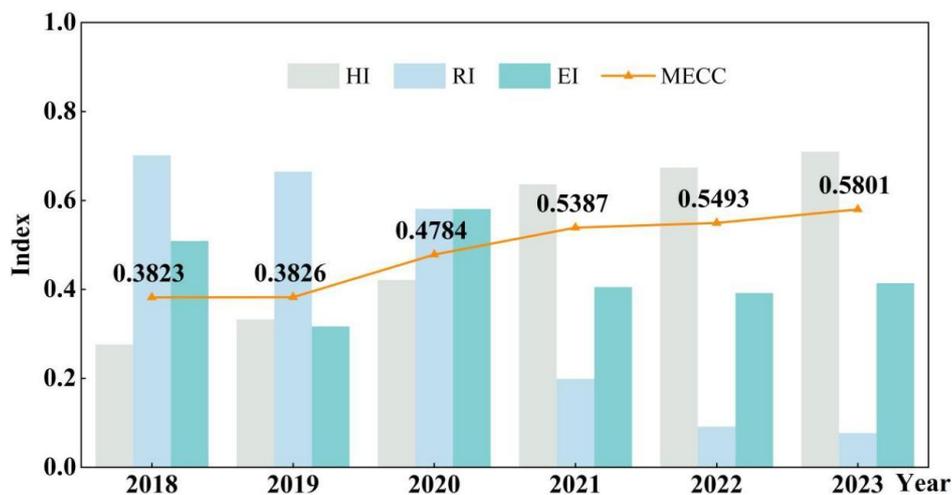


Figure 3. MECC and its various subsystem indices. MECC, Marine Ecological Carrying Capacity; HI, Human Socio-Economic Activity Index; RI, Resource Supply Capacity Index; EI, Environmental Pollution Absorption Capacity Index

The calculation results of HI, EI, and RI

Variations of HI

To further explore the reasons for the growth of the human socio-economic activity index, the indicators in this subsystem are divided into two categories according to their attributes: all positive indicators are defined as the support indexes, and all negative indicators are defined as the pressure indexes. The quantitative calculation results are shown in *Figure 4*. It can be seen that the pressure index showed an overall upward trend, increasing from 0.3486 in 2018 to 0.7148 in 2023, and decreased slightly to 0.3385 in 2019. In addition, its growth nearly stagnated from 2021 to 2022, only increasing slightly from

0.6562 to 0.6585. This indicates that compared with other years, human activities have slightly increased the pressure on the marine ecology in 2019 and 2022. The support index has rapidly increased rapidly between 2018-2019 and 2020-2021, indicating that humans have strengthened the protection of marine ecology in 2019 and 2021. Therefore, under the combined effect of pressure and support, the human socio-economic activity index in Jiaxing has showed an overall upward trend from 2018 to 2023. This indicates that human pressure on the ocean continued to decrease when the support continued to increase.

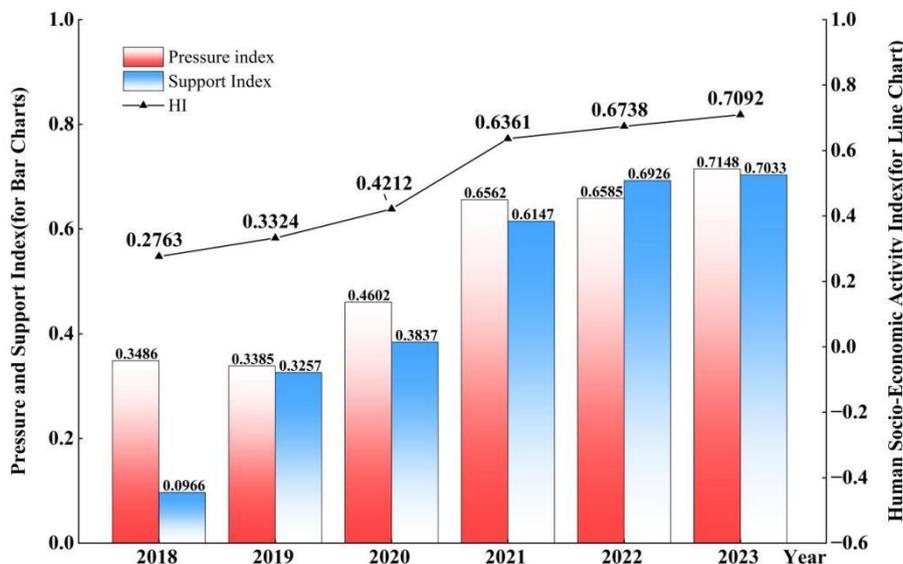


Figure 4. HI, pressure index, and support index. HI is calculated as the composite of the Pressure and Support sub-indices, reflecting the overall human-induced pressure on the marine ecosystem

Figure 5 reflects the changes in each indicator under the pressure index. The number of marine motor fishing vessels (Fig. 5f) and total marine catch (Fig. 5g) shows an overall upward trend, indicating that the pressure on the development of the marine fishery resource has decreased year by year. The cases studies of the Mediterranean Sea and Red Sea in Egypt show that strict fishing quantity control is the key to restoring fish stocks (Mamdouh-Lotfy et al., 2025). Discharging wastewater into the environment has led to a series of ecological problems (Venugopal and Sasidharan, 2021). The total amount of wastewater discharge (Fig. 5d) reached its lowest point in 2021 and then recovered rapidly in the following two years. This means that the pressure of marine pollution was alleviated during 2022-2023. The index of energy consumption per unit GDP (Fig. 5e) showed a fluctuating upward trend: it began to decrease in 2020, recovered rapidly in 2022, and reached its optimal value in 2023. This indicates that Jiaxing has achieved significant results in energy conservation and emission reduction. In addition, the natural population growth rate (Fig. 5a), number of tourists in coastal cities (Fig. 5b), and passenger turnover (Fig. 5i) showed an overall fluctuating upward trend, indicating that the pressure of population on MECC gradually decreased. However, the decrease in the indices of port cargo (Fig. 5c) and marine cargo turnover (Fig. 5h) indicates that marine economic activities have put considerable pressure on MECC.

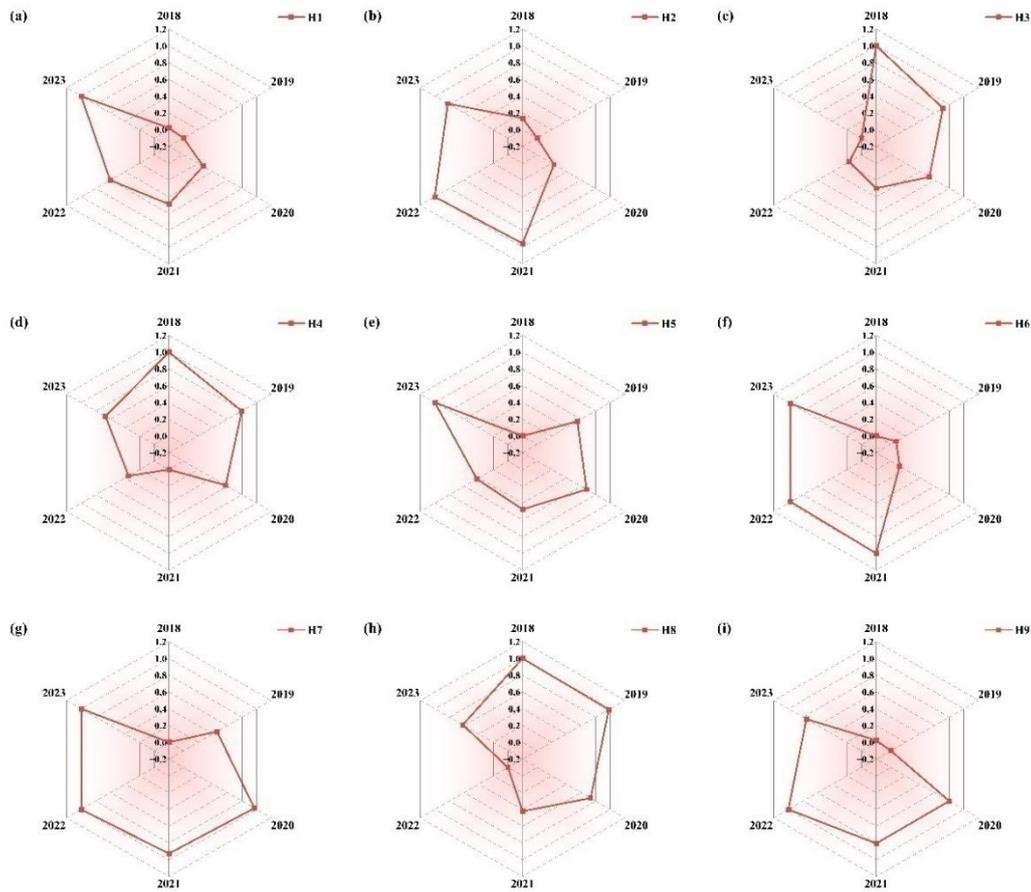


Figure 5. Specific changes indifferent pressure sub-indicators (2018-2023): (a) H1 (Natural population growth rate), (b) H2 (Number of tourists in coastal cities), (c) H3 (Port cargo throughput), (d) H4 (Total wastewater discharge), (e) H5 (Energy consumption per unit GDP), (f) H6 (Number of marine motor fishing vessels), (g) H7 (Total marine catch), (h) H8 (Marine cargo turnover), (i) H9 (Passenger turnover)

Figure 6 reflects the changes in each indicator under the support index. The stock enhancement index (Fig. 6a) showed the most obvious fluctuation trend: it increased to the highest value in 2019, then decreased continuously to the lowest value in the following two years, and resumed growth after 2021. This reflects the continuous optimization of stock enhancement measures, providing sustained support for the restoration of marine biodiversity. The area of marine protected areas (Fig. 6b) reached the optimal value in 2021 and remained stable thereafter. This indicates that the construction and management of protected areas have played a positive role in stabilizing the marine ecology. The establishment of marine protected areas is conducive to strengthening the protection of marine biodiversity (Baameur and Grimes, 2025; Motta et al., 2021). In terms of pollution control, the urban sewage treatment rate (Fig. 6c) continued to increase over time, reflecting the continuity of sewage treatment efforts. It can directly reduce the input of marine pollutants and effectively alleviate the pressure on the marine environment. However, the index of the proportion of environmental pollution control investment in GDP (Fig. 6d) showed a fluctuating trend: it decreased slightly in 2019, then recovered rapidly, reached the peak in 2020, and continued to decline thereafter. This indicates that a lack of momentum in environmental protection investment and a risk of a decline in

pollution control capacity. The number of personnel in scientific research and technology development institutions (*Fig. 6e*) decreased to its lowest point in 2019 and then increased year by year. This indicates that the Jiaxing government attaches great importance to scientific research and technology development, providing technical support for ecological restoration and protected area management.

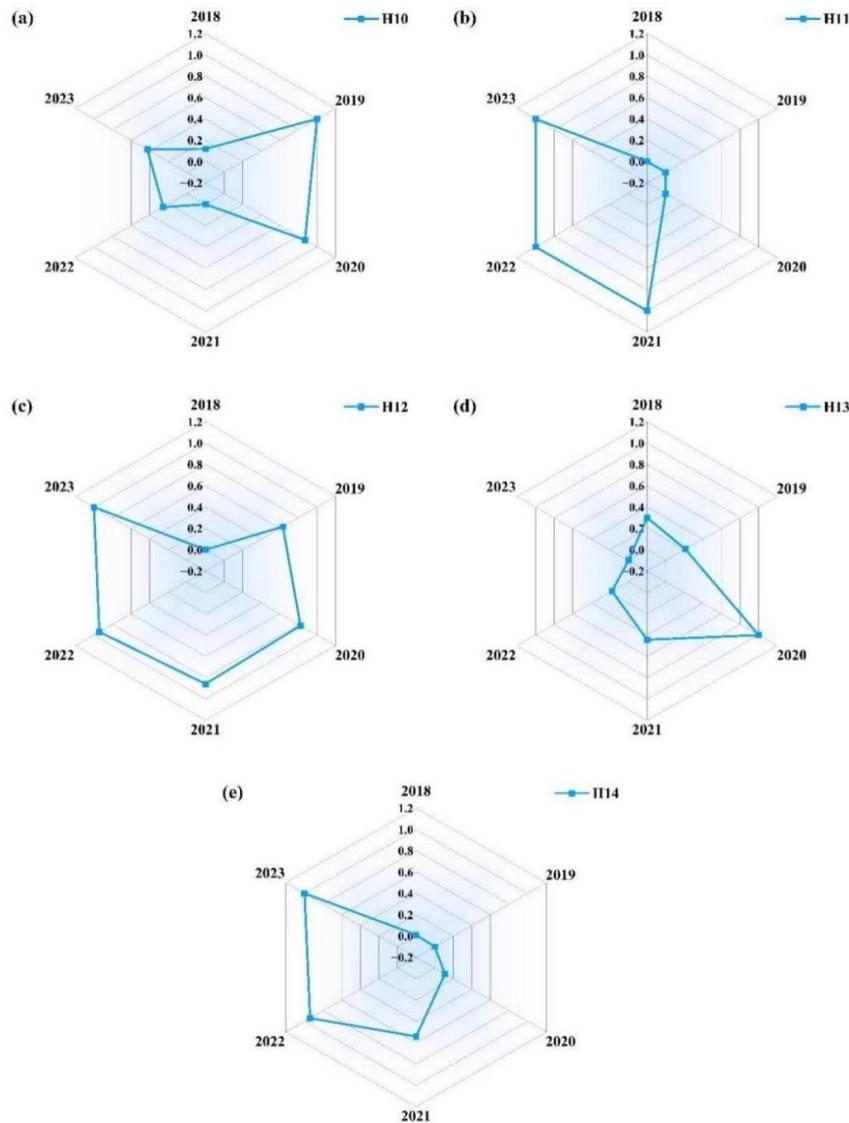


Figure 6. Specific changes in different support sub-indicators (2018-2023): (a) H10 (Quantity of stock enhancement), (b) H11 (Area of marine protected areas), (c) H12 (Urban sewage treatment rate), (d) H13 (Proportion of environmental pollution control investment in GDP), (e) H14 (Number of personnel in scientific research and technology development institutions)

Based on the comprehensive analysis of the index changes in *Figures 5* and *6*, the growth of human socio-economic activities is attributed to the significant enhancement of support and the continuous reduction of pressure. In particular, the establishment of marine protected areas, the continuous improvement of urban sewage treatment rate, and

the increase in scientific research and technology investment in 2021 have effectively offset the negative impacts of factors (such as pollution discharge and shipping pressure).

Variations of RI

Figure 7a shows that the marine resource supply capacity in Jiaxing has experienced a rapid downward trend, decreasing from 0.7009 in 2018 to 0.0770 in 2023, with an average annual decline rate of 35.71%. This indicates that the marine resources available for human use are continuously decreasing. The decline rate between 2020 and 2022 was significantly higher than in other periods, from 0.5809 to 0.0915, a staggering decrease of 84.25%. From the changes in the composition of the resource supply capacity index composition changes shown in Figure 7b, it can be seen that the per capita marine area index reached its peak in 2018 and then decreased year by year. The coastal tidal flat area grew rapidly from 2018 to 2019, reached its highest point in 2019, and then continued to decline. This reflects the increasingly prominent contradiction between the development and protection of marine spatial resources in Jiaxing during the urbanization process. This is highly consistent with the common problem of “tidal flat reclamation-ecological degradation” in Yangtze River Delta cities (such as Ningbo and Nantong) (Xu et al., 2018; Wang et al., 2022). The tourism revenue of coastal cities increased sharply from 2018 to 2019, reached its peak in 2019, then plummeted, and recovered slowly after 2022. This reflects the contribution of coastal tourism resources to the economy: the tourism market was prosperous in 2018-2019, and the tourism revenue declined significantly during 2020-2022 due to the impact of the epidemic.

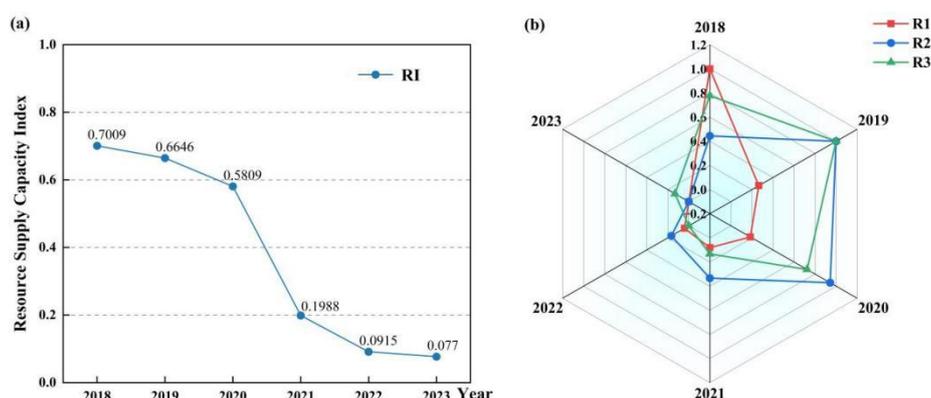


Figure 7. The changes in RI and its related indicators. The changes of RI and its related indicators in Jiaxing from 2018 to 2023 are shown. (a) Line chart presenting the index change trend of RI (Resource Supply Capacity Index during 2018-2023; (b) 3D radar chart, where the indicators correspond to: R1 (Per capita marine area), R2 (Coastal tidal flat area), R3 (Tourism income of coastal cities)

Variations of EI

As shown in Figure 8a, the marine environmental pollution absorption capacity of Jiaxing fluctuated within a certain range, decreasing slightly from 0.5086 in 2018 to 0.4140. This reflects that the function of the marine system in purifying pollutants is relatively stable. It can be seen from Figure 8b that from 2018 to 2019, all indices except for the reactive phosphate concentration index decreased. This indicates that the marine sediment environment deteriorated and the discharge of land-based pollution increased,

leading to a decline in environmental pollution absorption capacity during this period. From 2019 to 2020, the concentration of inorganic nitrogen, reactive phosphate, and phytoplankton diversity index reached the optimal values at the same time. This indicates that intervention effect of pollution control was significant, and the absorption capacity of environmental pollution was significantly improved. From 2020 to 2023, the concentration of inorganic nitrogen and phytoplankton diversity index decreased; that of reactive phosphate and zooplankton diversity index fluctuated abnormally, and the benthic organism diversity index remained at a low level. This indicates that there is a significant lag in the ecological effect of pollutant reduction. This is consistent with the law of “rapid effect of pollution control and long cycle of ecological restoration” in the Bohai Bay (Yu et al., 2021; Wang et al., 2020).

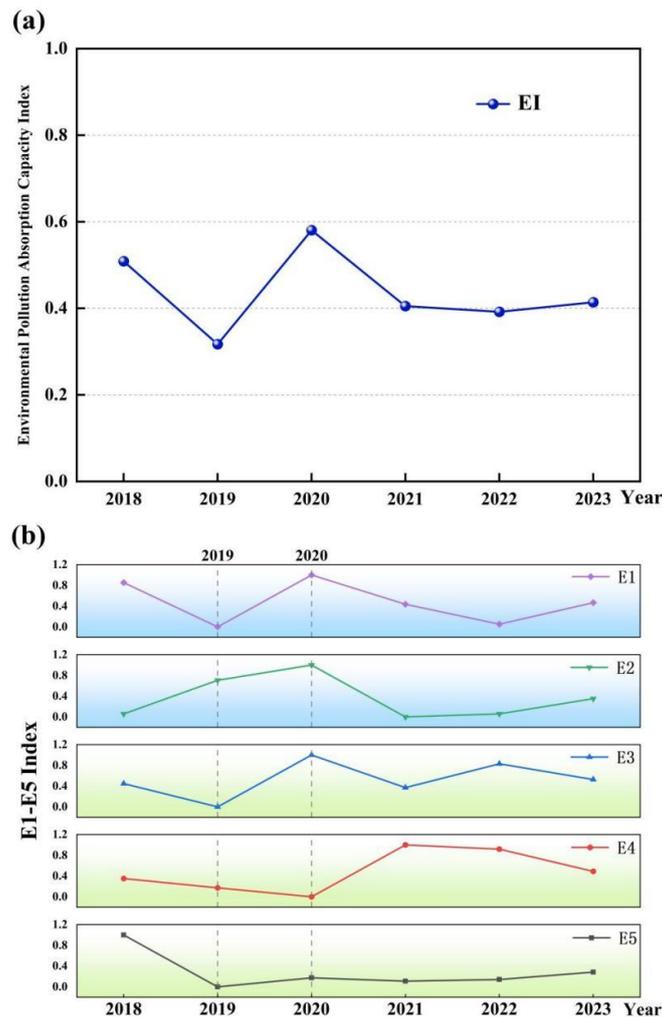


Figure 8. The changes in EI and its various indicators. The changes of EI and its related indicators in Jiaxing from 2018 to 2023 are shown. (a) Line chart presenting the index change trend of EI (Environmental Pollution Absorption Capacity Index) during 2018-2023; (b) Multiple line charts, where the indicators correspond to: E1 (Concentration of inorganic nitrogen), E2 (Concentration of reactive phosphate), E3 (Phytoplankton diversity index), E4 (Zooplankton diversity index), E5 (Benthic organism diversity index), presenting the index changes of these related indicators in 2018-2023

Conclusion

Based on the Pressure-State-Response (PSR) framework, we propose a conceptual model of MECC and constructed an MECC evaluation index system for Jiaxing. This study focuses on the interaction between humans and the ocean, systematically integrating various complex social, resource, and environmental variables. This model can effectively reflect the change trend of MECC in the study area. Based on the analysis of specific indicators, the key driving factors affecting the changes in MECC are further identified. The evaluation results show that the MECC of Jiaxing showed an upward trend from 2018 to 2023, with the key driving forces being the establishment of marine protected areas, the improvement of urban sewage treatment efficiency, and the enhancement of scientific research and technological support capabilities. These measures have significantly reduced the pressure of human socio-economic activities on the marine resource environment, strengthening the protection of marine ecology and promoting the sustainable development of Jiaxing. The case study in Jiaxing indicates that in coastal management, implementing protective policies, promoting environmental governance, and continuously investing in technological innovation constitute key ways to improve MECC.

In theory, this study enriches the dynamic research on the ecological carrying capacity of coastal cities and verifies the applicability of the “society-resource-environment” three-dimensional coupling model in small and medium-sized cities. In practice, the constructed evaluation framework can provide a basis for Jiaxing to formulate differentiated management and control strategies: in response to the shortage of resource supply, the red line for tidal flat protection should be strictly defined; long-term emission reduction assessment mechanism should be established to address fluctuations in environmental pollution absorption capacity; the experience of strengthening support in human socio-economic activities (such as establishing marine protected areas, optimizing stock enhancement, and increasing scientific research investment) can be promoted as key models for ecological restoration.

There is still a limitation that indicator data for some years rely on mean value estimation, and factors such as climate change, water flow, and sea level rise are not fully considered, which may affect the accuracy of the results. Future research should improve the evaluation index system, and deepen the analysis of driving mechanisms through combining long-term biological monitoring and mechanism models to enhance the comprehensiveness of the evaluation. This can provide more accurate scientific basis for the coordinated decision-making of ecological protection, resource utilization, and economic development in coastal cities, thereby better coordinating the harmonious coexistence between humans and nature, and achieving the sustainable development of coastal cities.

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