frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 25 November 2022
DOI 10.3389/fmars.2022.1009897

Check for updates

OPEN ACCESS

EDITED BY
Kum Fai Yuen,
Nanyang Technological University, Singapore

REVIEWED BY
Peng Zhang,
Guangdong Ocean University, China
Mei Xuefei,
East China Normal University, China

*CORRESPONDENCE
Dongliang Lu
ldl@bbgu.edu.cn
Yuping Xu
xuyuping@bbgu.edu.cn

SPECIALTY SECTION
This article was submitted to Marine Affairs and Policy, a section of the journal Frontiers in Marine Science

RECEIVED 09 August 2022
ACCEPTED 07 November 2022
PUBLISHED 25 November 2022

CITATION
Zhou J, Wang X, Lu D, Dan SF, Kang Z, Xu Y, Weng P and Wei Z (2022) Ecological security assessment of Qinzhou coastal zone based on Driving forces-Pressure-State-Impact-Response (DPSIR) model.
Front. Mar. Sci. 9:1009897.
doi: 10.3389/fmars.2022.1009897

Ecological security assessment of Qinzhou coastal zone based on Driving forces-Pressure-State-Impact-Response (DPSIR) model

Jiaodi Zhou[1], Xilong Wang[1], Dongliang Lu[1*], Solomon Felix Dan[1], Zhenjun Kang[1], Yuping Xu[2*], Peiyao Weng[3] and Zhaofu Wei[4]

[1]Guangxi Key Laboratory of Marine Environmental Change and Disaster in Beibu Gulf, Beibu Gulf University, Qinzhou, China, [2]Beibu Gulf Ocean Development Research Center, Beibu Gulf University, Qinzhou, China, [3]Oceanic Bureau of Qinzhou, Qinzhou, China, [4]Guangxi Academy of Oceanography, Nanning, China

A coastal zone represents the intersection of ocean and land, and is characterized by high primary productivity, biodiversity, and rich resources but with strong sensitivity and vulnerability of the natural environment. In this study, 29 indicators reflecting the status of ecological security were selected to construct an ecological security evaluation index system using the Driving force Pressure State Impact Response (DPSIR) model. The comprehensive index method was used to evaluate the ecological security of Qinzhou coastal zone from 2011 to 2020 and to explore the driving factors of its evolution. The results showed that (1) In the past 10 years, the ecological security of Qinzhou coastal zone fluctuated and developed, and the security level changed from early warning – safer – more dangerous – early warning to safer; and the security level was the lowest (0.361) in 2014. The main reason was the impact of ecological marine disasters, such as three red tides with the eutrophication index of seawater as high as 4.170. (2) Since 2015, the ecological security of the coastal zone has shown an upward trend, which was mainly due to the implementation of the newly revised environmental protection law in the same year, the comprehensive promotion of "The 13th Five-Year Plan for environmental protection", and a series of measures related to the construction of ecological civilization and environmental protection, which provided a strong guarantee for the ecological security of the coastal zone. This study proposes measures to promote the better development of the ecological environment of Qinzhou coastal zone.

KEYWORDS

coastal zone, ecological security assessment, ecosystem conservation, DPSIR model, Qinzhou City

1 Introduction

Coastal zones are characterized by high productivity, biodiversity, and rich resources, which are valuable from both economic development and ecological perspectives. However, these zones are fragile because of their location in an active area sensitive to human activities and rapid economic growth. With increased industrialization and development of the coastal economy in recent years, a series of serious problems, which pose safety risks to human and environmental health, including inefficient resource utilization, and reduced carrying capacity of the ecological environment, has emerged in coastal zones. In the outline of "The 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China", proposals include strengthening the comprehensive management of coastal zones, improving coastline protection, exploring the coastal building retreat line system, and ensuring that the preservation rate of natural coastlines is not less than 35% (The People's Republic of China, 2021). However, due to the continuous social and economic development in Qinzhou coastal zone, human activities involving the use of resources and space from the sea have synchronously increased. All these have contributed to the degradation of ecological functions, increased resource destruction and environmental pollution, and a decrease in wetlands and natural shorelines in Qinzhou coastal zone. Therefore, a comprehensive study of the coastal zone is necessary. The ecological security evaluation of a coastal zone is one of the most critical aspects of the comprehensive study of coastal zones to curb the deterioration of the marine ecological environment, promote marine ecological civilization construction, and improve the development ability of coastal zones, which can be achieved by fostering controlled and integrated management systems.

Research on the ecological security of coastal zones has intensified in many parts of the world due to serious environmental problems in coastal zones. In China, most studies have primarily focused on three aspects, i.e., safety management, current situation evaluation, and pattern planning, respectively (Fabbri, 1998; Wu et al., 2012; Jiao et al., 2015). The contents included coastal zone ecological security management mechanisms, ecological security status analysis, ecological security evaluation model, and forecast with good optimization of the environmental pattern of China (Xu et al., 2016; Lu et al., 2019; Su et al., 2020; Zong et al., 2021). The management model was set up by many scholars (Mokhtar and Aziz, 2003; Banerjee et al., 2016) in line with China's coastal zone ecological security from the perspective of ecological security management methods and environmental problems. Based on 10 major ecological and environmental problems affecting China's coastal zone, combined with the progress and trend of international research, new ideas for the sustainable development of the country's coastal zone were discussed (Wang, 2003; Liu et al., 2020; Liang and Li, 2020), and various assessment models were used to study the temporal and spatial changes of coastal ecological security (Wei et al., 2014; Ersha et al., 2017; Bi et al., 2020; Gao et al., 2022; Cheng et al., 2022). The ecological security of the coastal zone has been studied in different countries, primarily in the aspects of integrated coastal zone management, environmental evolution and disaster forecast, and ecosystem risk assessment (Beatley et al., 2002; Yanes et al., 2019; Jian et al., 2020). The method and tool for decision-making on integrated coastal zone management have been improved in some studies (Jian et al., 2012; Alves et al., 2013; Xiao et al., 2018), which discusses the advantages of executing the most effective data capture, integration, analysis, and modeling strategies in spatial decision support systems to evaluate the impact of possible development scenarios (Fabbri, 1998; Westmacott, 2001; Shipman and Stojanovic, 2007). The dynamics of coastlines and related landscape change rates of different land-use and land-cover modes have been studied by digital coastline analysis systems (Yang et al., 2008; Abdullah et al., 2019; Jana, 2020), and the analytic hierarchy process (AHP) and geographic information system have been used to evaluate the coastal vulnerability index of the coastlines (Bera et al., 2019; Rajakumari et al., 2022; Morsy et al., 2022). Despite all these studies, there is a limitation in human understanding of the complex relationship and interaction mechanism between various parts of the coastal zone ecosystem, partly due to the lack of comprehensive research on the coastal zone system. Due to this limitation, a Driving force Pressure State Impact Response (DPSIR) model was employed in this study to quantify the evaluation value and prediction of coastal ecological security from the perspective of complex coastal ecosystems. The purpose is to accurately grasp the ecological security situation of the Qinzhou coastal zone and objectively evaluate the ecological security. On this basis, the dynamic evolution trend of ecological security under the future development situation was assessed and analyzed to provide countermeasures and suggestions for the ecological environment protection of Qinzhou coastal zone. Such proposals can ensure the social and economic sustainable development of Qinzhou City and the construction of Qinzhou Port Free Trade Zone.

2 Materials and methods

2.1 Study area

Qinzhou (Figure 1) is located in southwest China, next to Nanning, the capital of Guangxi, in the north and south of the Guangxi Zhuang Autonomous Region and along the Beibu Gulf Coast. It is linked to Beihai City and the Yulin area in the east and Fangchenggang City in the west. Qinzhou is located close to the broad Qinzhou Bay, with a sea area of 908.37 km^2 (Gu et al., 2015). Qinzhou Bay is part of the Beibu Gulf, South China Sea, and is located in the northernmost part of the fish-rich Beibu Gulf. Qinzhou Bay starts from Yingluo Port of Hepu County in the East and ends at Beilun estuary of

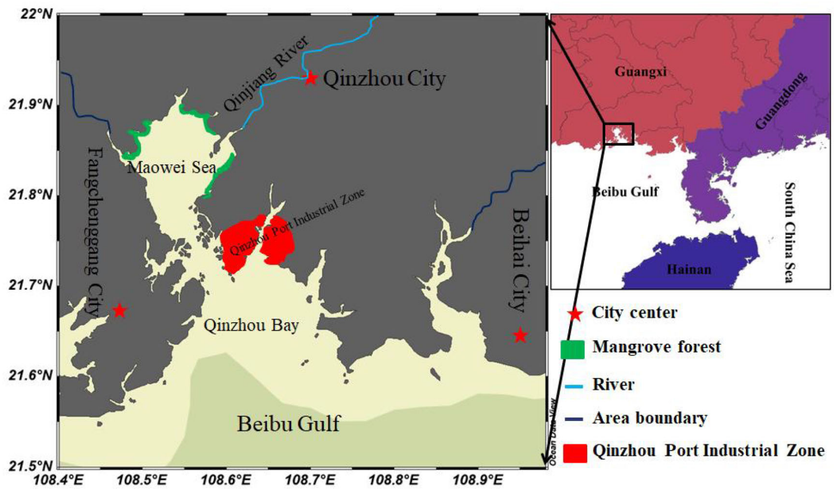

FIGURE 1
Map showing the geographical location of the study area.

Fangcheng County in the west, with a coastline of 1478 km. In 2020, Qinzhou had a permanent resident population of about 3.3 million, a gross domestic product (GDP) of 13.87 ten billion yuan, and has gradually built a development pattern dominated by five industries, i.e., petrochemical, equipment manufacturing, electronic information, food processing, and papermaking and biomedicine (Xu et al., 2019). These industries included China-Malaysia Qinzhou Industrial Park, China Shipbuilding offshore wind power industrial base, Jingui pulp and paper enterprises, and the ASEAN natural medicine and plant medicine industry development platform. Qinzhou is a key developmental area for urban construction and economic growth of the future Beibu Gulf Economic Circle (Xu et al., 2019).

2.2 Data sources and research methods

The original data of the indicators used in this study were obtained from 2011 to 2020 from Qinzhou Statistical Yearbook (http://www.qinzhou.gov.cn), the bulletin of Qinzhou environmental statistics (http://qinzhou.gov.cn), the bulletin of marine environmental quality of Guangxi Zhuang Autonomous Region (http://gxzf.gov.cn), the bulletin of marine disasters in Guangxi (http://gxzf.gov.cn), China marine environment quality bulletin (http://www.nmdis.org.cn), China sea level bulletin (http://www.nmdis.org.cn), China marine disaster bulletin (https://www.nmdis.org.cn/hygb/zghyzhgb/), and Qinzhou marine environment monitoring and prediction centre.

2.3 Analysis and evaluation methods

2.3.1 Seawater eutrophication index

Seawater eutrophication index is one of the standard methods employed in evaluating the quality of seawater (Jiang and Fang, 2009; Yong, 2016; Lin et al., 2021). It is expressed as the following equation:

$$EI = \frac{COD_{Mn} \ast DIP \ast DIN}{4500} \ast 10^6 \tag{1}$$

where EI is the eutrophication index; COD_{Mn}, DIP, and DIN are the measured values of chemical oxygen demand, dissolved inorganic phosphorus, and dissolved inorganic nitrogen, respectively. DIN is the sum of nitrite nitrogen, nitrate nitrogen, and ammonia nitrogen. In this study, EI is interpreted according to the technical specification for offshore environmental monitoring (HJ442.10-2020), as shown in Table 1.

2.3.2 Heavy metal pollution index of seawater

Heavy metal pollution is often due to the combined pollution of multiple elements in water, but a single evaluation index cannot fully reveal the status of heavy metal pollution in the water. The average pollution degree of each pollutant and the most serious pollution factors can be evaluated using the Nemero composite index method, which effectively avoids the influence of subjective factors on the weighting process. This method has been widely used to evaluate the environmental quality of water (Chen et al., 1991; Zhang and Wen, 2008; Yang et al., 2015) using the following equations.

TABLE 1 Standards for classification of water eutrophication.

Water quality grade	Poor nutrition	Mild eutrophication	Middle eutrophication	Heavy eutrophication	Severe eutrophication
EI	$EI < 1.0$	$1.0 \le EI < 2.0$	$2.0 \le EI < 5.0$	$5.0 \le EI < 15.0$	$EI \ge 15.0$

Single factor pollution assessment:

$$A_i = \frac{C_i}{B_i} \quad (2)$$

Nemero composite pollution index:

$$H_n = \sqrt{(A_{i\max}^2 + \bar{A}^2)/2} \quad (3)$$

$$\bar{A} = \frac{1}{n}\sum_{i=1}^{n} A_i \quad (4)$$

where i refer to heavy metals in different water bodies, A_i is the pollution index of each element; C_i is the measured concentration of i pollutants, and B_i is the evaluation standard of pollutants based on class II of seawater quality standard (GB3097-1997). $A^2{}_{i\ \max}$ and A^{-} are the maximum pollution index of all elements and the average value of the pollution index, respectively. According to the Nemero composite index, the quality of water can be divided into five grades, as shown in Table 2.

2.4 Ecological security evaluation index system of Qinzhou coastal zone

2.4.1 Construction of index system

This study adopts the DPSIR model framework to quantify the evaluation value and prediction of coastal ecological security in the Qinzhou coastal zone. According to the unique natural attributes and ecological problems of the coastal zone, the formation mechanism of coastal zone ecological risk and the need for ecological environment protection were fully considered. The coastal zone ecological security was summarized into driving force, pressure state, and impact and response. Combined with the ecological security evaluation index system and the specific situation of Qinzhou coastal zone, 29 factors that reflect the characteristics of the ecological security were selected to construct the ecological security evaluation index system of this coastal zone, as shown in Table 3.

2.4.2 Standardization of indicators

The various evaluation indicators do not have a uniform scale and unit and cannot be compared directly. Thus, the raw data of these indicators were standardized by the polar difference method to ensure dimensionality. The positive and negative indicators were converted according to Eq. 5 and Eq. 6, respectively.

Positive indicators:

$$X'_{ij} = \frac{X_{ij} - X_{jmin}}{X_{j\max} - X_{j\min}} \quad (5)$$

Negative indicators:

$$X'_{ij} = \frac{X_{j\max} - X_{ij}}{X_{j\max} - X_{j\min}} \quad (6)$$

where, X_{ij},X'^{ij} denotes the original and normalized values of the j indicator in the year i respectively; and X_{jmax} and X_{jmin} denote the maximum and minimum values of each indicator in j, respectively.

2.5 Research methods

The subjective evaluation tendency of the expert scoring method was avoided, and purely objective assignment characteristics of the entropy method were adopted. In this study, hierarchical analysis and entropy methods were employed to determine the subjective weights (Y_{1j}) and objective weights (Y_{2j}) of the indicators.

2.5.1 Entropy method

The entropy method is a commonly used method for objective weighting. It depends entirely on the relationship of

TABLE 2 Classification criteria for Nemero composite index (Hn).

Pollution index level	Pollution index	Pollution degree	Pollution level
1	Hn ≤ 0.7	Safety	Clean
2	0.7< Hn ≤ 1.0	Warning line	Fairly clean
3	1.0< Hn ≤ 2.0	Light pollution	When the pollutants exceed the initial Pollution value, the water body begins to be polluted
4	2.0< Hn ≤ 3.0	Medium pollution	Obvious water pollution

TABLE 3 Ecological security evaluation index system of coastal zone based on DPSIR model.

Criterion layer	Indicator layer	Measuring unit	Indicator attribute
Socio-econoiceconomic driving force (D)	H1 Total output value of tertiary industry	100 million yuan	+
	H2 Ratio of industrial output value to GDP	%	+
	H3 Per capita disposable income of urban residents	yuan	+
	H4 Population density	Person/sq. km	–
	H5 Per capita water resources	m^3/person	+
	H6 Total output of marine products (fishing and aquaculture)	t	+
Socioeconomic Pressure (P)	H7 GDP energy intensity	t	–
	H8 Number of domestic tourists	10,000 person times	–
	H9 Density of marine garbage	kg/km^2	–
	H10 Mariculture area	hm^2	–
	H11 Fertilizer application intensity	kg/hm^2	–
	H12 Seawater eutrophication index	\	–
	H13 Number of typhoon storm surge disasters	times	–
Status of marine resource (S)	H14 Annual precipitation	mm	+
	H15 Primary productivity - chlorophyll a content	μg/L	–
	H16 Macrobenthic biodiversity index	\	+
	H17 Forest coverage	%	+
	H18 Heavy metal pollution index of seawater	\	–
Marine environmental influence (I)	H19 Sea level change	mm	–
	H20 Annual average temperature in coastal areas	°C	–
	H21 Excellent rate of ambient air quality	%	+
	H22 Chemical oxygen demand emissions	t	–
	H23 Loss of major marine disasters in coastal areas	100 million yuan	–
Socioeconomic response (R)	H24 Total sewage treatment	10,000 tons	+
	H25 Coastline port throughput	10,000 tons	+
	H26 General public budget expenditure (energy conservation and environmental protection)	10,000 yuan	+
	H27 Harmless treatment rate of domestic waste	%	+
	H28 Standard rate of sewage discharged	%	+
	H29 Greening coverage rate of built-up area	%	+

The symbols "–" and "+" are used to represent negative and positive indicator attributes, respectively.

the evaluation index data to form a judgment matrix, which is used to calculate the entropy and determine the weight of each index so that the subjective influence of people can be minimized. Here, the greater amount of information with uncertainty results in smaller entropy, while higher entropy would occur when there is a small amount of information with uncertainty. Therefore, information from entropy can be used to calculate the weight. Due to the variation degree of each index, the weight of each index was calculated by using the information entropy tool, which provides a basis for comprehensive multi-index evaluation. The calculation steps of the entropy method were as follows:

Weight X'_{ij} of indicator P_{ij}:

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} X'_{ij}} \tag{7}$$

Entropy value E_j for jth indicator:

$$E_j = -(\frac{1}{Inn})\sum_{i=1}^{n} P_{ij} In P_{ij} \tag{8}$$

Coefficient of variability Dj for jth indicator:

$$D_j = 1 - E_j \tag{9}$$

Weight Y_{1j} for jth indicator:

$$Y_{1j} = \frac{D_j}{\sum_{j=1}^{n} D_j} \tag{10}$$

2.5.2 Hierarchical analysis method

AHP is a typical multi-level weight decision-making method that is often used in the multi-index comprehensive evaluation of several indicators. It can quantify qualitative factors, use mathematical expressions to deduce the subjective judgment of researchers, test and reduce the subjective influence of researchers, and make the final evaluation results more scientific and rational. In questionnaires, the evaluation indicators were scored according to experts in the field of marine protection in Guangxi, and the subjective weight value Y_{2j} of each indicator was calculated using SPSS19.

2.5.3 Portfolio empowerment

In portfolio empowerment, the combination of subjective and objective weights, to a certain extent, can avoid the decisive role of subjective cognition and evaluation of the AHP and the limitations of the entropy method. The combined weight of each index in the ecological security index system of Qinzhou City was obtained (Figure 2) using Eq. 11 and the results are shown in Table 4.

The formula for calculating the weight Y_j of the jth indicator combination is

$$Y_j = \frac{\sqrt{Y_{1j} Y_{2j}}}{\sum_{j=1}^{n} \sqrt{Y_{1j} Y_{2j}}} \tag{11}$$

where n is the total number of indicators Y_{1j} is the entropy method weightand Y_{2j} is the hierarchical analysis method weight.

2.6 Evaluation index of the comprehensive ecological safety

The comprehensive index of Qinzhou coastal zone ecological safety Z_i was calculated for the year i based on the statistical data and the weights of the calculated indicators using Eq 12.

$$Z_i = \sum_{j=1}^{n} X'_{ij} Y_j \tag{12}$$

where Z_i takes values in the range of [0, 1]. The nearer the score is to 1, the higher the grade of the ecological safety status of the coastal zone, and vice versa, the lower it is. The ecological safety status of the coastal zone can be divided into five grades according to relevant studies (Jian et al., 2012; Ye and Yaoqiu, 2020) (Table 5).

3 Evaluation results and analysis

3.1 Results of the ecological safety evaluation of the Qinzhou coastal zone

A comprehensive assessment of the marine ecological security in Qinzhou City is conducted based on data from 2011 to 2020. The basic evolution of its coastal zone ecological safety by DPSIR framework is shown in Figure 2. The proportion of each index is shown in Figure 3. According to coastal zone ecological safety status, the coastal zone ecological safety composite index in Qinzhou City showed a fluctuating upward trend from 2011 to 2020. In the past 10 years, the lowest ecological safety index was 0.361 in 2014, and the highest was 0.648 in 2018. The safety status of the coastal zone in Qinzhou City continuously changed from a warning (i.e., more dangerous) to a safer status after 2016 (Figure 2).

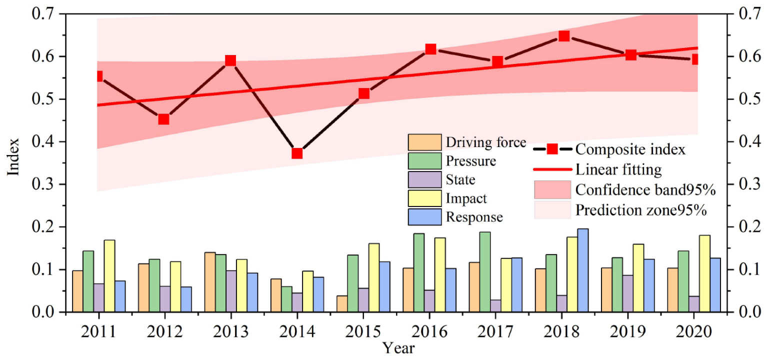

FIGURE 2
Evaluation results of the ecological security of the Qinzhou coast.

TABLE 4 Weight evaluation indicators of coastal ecological security in Qinzhou City.

Target level	Guideline level	Indicators	Entropy method	Hierarchical analysis	Portfolio weights
Assessment of coastal zone ecological safety	D	H_1	0.0104	0.0327	0.0224
		H_2	0.0009	0.0345	0.0068
		H_3	0.0057	0.0352	0.0172
		H_4	0.0767	0.0361	0.0640
		H_5	0.0192	0.0354	0.0317
		H_6	0.0735	0.0373	0.0637
	P	H_7	0.0168	0.0357	0.0298
		H_8	0.0142	0.0371	0.0279
		H_9	0.0772	0.0374	0.0654
		H_{10}	0.0011	0.0339	0.0074
		H_{11}	0.0395	0.0358	0.0457
		H_{12}	0.0354	0.0316	0.0407
		H_{13}	0.0120	0.0370	0.0256
	S	H_{14}	0.0002	0.0358	0.0033
		H_{15}	0.0232	0.0246	0.0291
		H_{16}	0.0038	0.0361	0.0142
		H_{17}	0.0010	0.0343	0.0071
		H_{18}	0.0743	0.0366	0.0634
	I	H_{19}	0.0549	0.0339	0.0525
		H_{20}	0.0064	0.0375	0.0188
		H_{21}	0.0140	0.0346	0.0268
		H_{22}	0.0272	0.0372	0.0387
		H_{23}	0.1978	0.0249	0.0854
	R	H_{24}	0.0039	0.0347	0.0141
		H_{25}	0.0017	0.0349	0.0094
		H_{26}	0.0095	0.0373	0.0229
		H_{27}	0.0999	0.0335	0.0704
		H_{28}	0.0755	0.0376	0.0648
		H_{29}	0.0240	0.0268	0.0308

3.2 Analysis of evaluation results

The weights were used to measure the importance of each evaluation indicator to the ecological safety of the coastal zone of Qinzhou. The more significant the weight is, the greater the influence. Based on the results of the weight distribution, the top 10 indicators in terms of influence from the largest to the lowest were loss of major marine disasters in coastal areas > harmless treatment rate of domestic waste > density of marine waste > compliance rate of outfalls > population density > total production of seawater products (fishing and breeding) > comprehensive pollution index of heavy metals in water bodies > amount of sea-level change > intensity of fertilizer application and eutrophication index of seawater. These indicators were the main causes of changes in the ecological environment of the coastal zone of Qinzhou City. The following were analyzed from the five main aspects of DPSIR.

3.2.1 D-index

The change of the coastal zone drive index in Qinzhou City from 2011 to 2020 fluctuated and tended to be stable. The rising Qinzhou drive index increased from 0.097 in 2011 to 0.140 in 2013, falling to 0.038 in 2015, and then slightly starting from 0.103 in 2016 with fluctuations to an index of 0.103 in 2020

TABLE 5 Levels of coastal zone ecological security.

Level	I	II	III	IV	V
State	Safety	Safer	Early Warning	A little dangerous	Dangerous
Z_i	(0.75~1.00]	(0.55~0.75]	(0.45~0.55]	(0.25~0.45]	(0.00~0.25]

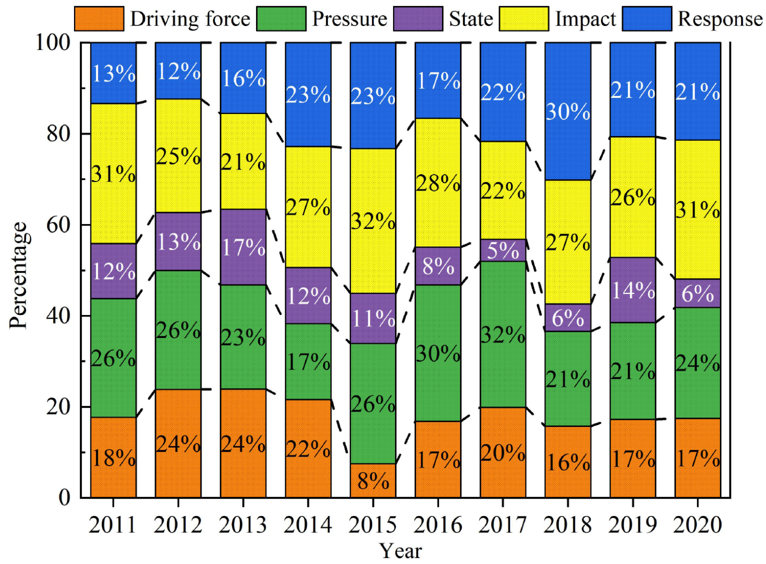

FIGURE 3
Percentage of each indicator (DPSIR) of the coastal zone ecological safety evaluation system in Qinzhou.

(Figure 2). The driving force accounted for 18.50% of the overall ecological safety evaluation system; the lowest percentage (8.00%) occurred in 2015 (Figure 3). This result indicates that the degree of contribution of driving force indicators to the ecological safety Qinzhou coastal was constantly changing. Under the layer of driving force indicators, the top 10 weighted individuals accounted for 20% and influenced ecological safety. The total output values of tertiary industry, per capita disposable income of urban residents, population density, and total output of marine products (fishing and aquaculture) increased by 169%, 56%, 422% and 17% from 2011 to 2020, respectively. The ratio of industrial output value to GDP and per capita water resources decreased by 37% and 52% from 2011 to 2020, respectively. This suggests that increase in population, human activities, and demand for seafood are promoting economic development of coastal zone while also bringing pressure on the environment and resources.

3.2.2 P-index

The stress index decreased slowly from 0.144 in 2011 to 0.060 in 2014 but increased sharply from 0.134 in 2015 to 0.189 in 2017. Then, it decreased to 0.128 in 2019 and gradually increased to 0.144 in 2020 (Figure 2). All indicators in the stress criterion layer were negative (Table 3). Thus, the coastal zone ecosystem was mostly stressed in 2014, and the main impacting indicators were seawater eutrophication index and marine litter density. Seawater eutrophication index and marine litter density increased by 26% and 333% from 2011 to 2020, respectively. Both indicators reached their peaks during the decade, indicating that the extent of human impact on the coastal zone has been intensely increasing with rapid economic development. The stress index gradually increased from 2015 and peaked in 2017. This result indicates that stress index was improved during this time, mainly due to a significant decrease in seawater eutrophication index and the intensity of fertilizer application. In 2017, seawater eutrophication index and density of marine garbage were 65.54% and 80.76% lower than that in 2014, respectively. The pressure index showed a slowly increasing trend from 2018 to 2020 mainly due to the increasing number of domestic tourists. About 25,711,800 domestic tourists were received in 2017; in 2020, the number of domestic tourists received increased by 50.73%. The largest share of stress index over the decade was 32% in 2017, indicating that the combined index was most affected by stress throughout 2017. In recent years, the construction of coastal parks and national mangrove nature reserve attracted a large number of tourists, and tourists and marine litter density respectively increased by 400% and 333% from 2011 to 2020.

3.2.3 S-index

From the S-index perspective, the changing trend fluctuated with a large range from 2011 to 2020. The highest state index was 0.097 in 2013, while the lowest state index was 0.028 in 2017, showing an approximately 71.1% reduction mainly because the seawater heavy metal pollution index was a negative indicator. In 2013, the lowest index was 0.21, indicating that seawater was clean and safe. Still, the index reached a maximum of 1.29 (light pollution) in 2017, which indicated that seawater started becoming polluted (Table 2). The content of primary productivity, as shown by chlorophyll-*a*, varied considerably from 3.79 μg/L in 2013 to 5.79 μg/L in 2017. The higher the rate of this indicator, the more serious the eutrophication of seawater was. The 2020 state index was relatively low mainly because microbenthic diversity index decreased from 2.17 in 2017 to 0.39 in 2020. Overall, the state index accounted for a relatively low proportion (approximately 10%) of the coastal zone ecological safety evaluation system, which indicated a lower impact on ecological safety evaluation.

3.2.4 I-index

The impact index was the smallest, i.e., 0.096 in 2014 and 0.119 in 2017 but remained at approximately 0.15 in all other years. The main reason for this is that the major marine disaster losses in the coastal region peaked in 2014 with losses of about 3.04 billion yuan, and this index has a weight of 0.08, ranking first in the weighting order. A review of the relevant historical data revealed that Qinzhou experienced two storm surge disasters at the time, namely, Super Typhoon 1409 "Rammasun" and Typhoon 1415 "Kalmaegi", There was one major water quality anomaly, while other years saw marine disaster losses. The change in sea level was the largest in 2017, reaching 108 mm, an increase of 55.50% compared to 2011 when the change in sea level was the smallest. In 2017, the good ambient air quality rate was lower, falling by 11.59% compared to the rate (99.20%) in 2020. Overall, the impact index accounted for the most significant proportion of the ecological safety evaluation system, averaging 27%. Therefore, it plays a major role in assessing the ecological safety of the coastal zone.

3.2.5 R-index

The response index displayed a fluctuating upward trend from 2011 to 2020, but there was a convex increase in 2018, mainly due to the large increase in the rate of outfall compliance and general public budget expenditure (e.g., energy conservation and environmental protection). As the rate of outfall compliance reached its highest value in 2018, the response index increased by 32.94% compared to that in 2016. The general public budget expenditure peaked in 2018, with an investment of 187 million yuan, as the government increased its investment in energy conservation and environmental protection. The domestic waste treatment rate has reached 100% since 2015, indicating that the importance of ecological environment protection in Qinzhou coastal zone and city has been strengthened, and the measures taken have produced significant results. Overall, the response index accounted for the most significant proportion of the coastal zone ecological safety evaluation system in 2018 at 30%, while other years accounted for approximately 18.67%.

3.3 Comparison and analysis with other regions

Qinzhou Bay is a semi-enclosed bay for industry, agriculture, and tourism. In recent years, with the rapid development of coastal industries and increasing human activities, the coastal zones in Qinzhou are facing various severe threats, such as water quality decline, overfishing and harvesting, and biodiversity loss (Bryan-Brown et al., 2020). Moreover, the areas of coastal zones are decreasing sharply around the world, and the functions of coastal zones are also deteriorating, resulting in considerable ecological and economic losses. Population growth, urbanization, and competition for resources, transport, and energy are putting upward pressure on coastal zones (Chen et al., 2022). The comprehensive index of Qinzhou coastal zone and a comparison with other regions are shown in Table 6. Results show that the comprehensive index of Sanya City, Daya Bay, Guangdong/Hong Kong/Macao, and Qinzhou coastal zone tends to the trend of good development, mainly due to the national marine ecological environment protection policy, such as "Marine Environmental Protection Law of the People's Republic of China in 2020 and "The 13th Five-Year Plan for Marine ecological and environmental protection" etc. The comprehensive ecological index of Qinzhou Bay is lower than that of other regions (Table 6), mostly due to geography. The other survey areas are located in the open sea, while Qinzhou Bay is located in the inner bay, where hydrodynamics is relatively weak, and the input of many rivers in Qinzhou Bay results in a relatively poor ecological environment for the Qinzhou coastal zone.

TABLE 6 Comprehensive index of Qinzhou coastal zone compared to other regions.

Survey region	Research method	Comprehensive index (Time)	References
Sanya City	DPSIR	0.179(2014), 0.321(2015), 0.514(2016), 0.7457(2017), 0.719(2018)	Li and Yan, 2021
Daya Bay	DPSIR	0.467(2007), 0.489(2010), 0.503(2013), 0.658(2015), 0.638(2016)	He and Kuang, 2020
Guangdong/Hong Kong/Macao	DPSIR	0.356(2001), 0.616(2005), 0.614(2010), 0.622(2015), 0.584(2018)	Gao et al., 2022
Qinzhou coastal zone	DPSIR	0.549(2011), 0.476(2012), 0.588(2013), 0.361(2014), 0.507(2015), 0.616(2016), 0.586(2017), 0.648(2018), 0.602(2019), 0.591(2020)	This study

4 Conclusions and recommendations

4.1 Conclusions

This study draws the following three conclusions through the construction of indicators and ecological safety evaluation: (1) The ecological safety level of the coastal zone of Qinzhou City from 2011 to 2020 can be divided into three change segments: from 2011 to 2013, warning (III) - safer (II); in 2014, more dangerous (IV); from 2015 to 2020 warning (III) - safer (II). The safety level has fluctuated upward over the past 10 years. (2) Although overall ecological safety measures were improving, the ecological indicators such as ecological diversity and air quality still showed a downward trend. (3) Due to the limited availability of data, the coastal zone ecosystem indicator system needs to be further improved.

4.2 Recommendations

Qinzhou City has made considerable achievements in coastal zone management in the past decade. However, certain limitations exist in coastal zone protection and law enforcement, management coordination, planning, etc. Based on the actual problems of Qinzhou city's coastal zone combined with the national and local levels, the suggestions to systematically carry out the ecological health protection of the coastal zone are as follows: (1) Reinforcement of the construction of the coastal zone legal system; (2) Multi-departmental joint preparation of comprehensive coastal zone planning; (3) Strengthening coastal zone ecological restoration technology; (4) Optimizing the ecological safety evaluation system; (5) Strengthening publicity and providing continuous public participation; and (6) Improving the coastal zone ecological compensation mechanism.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

JZ: conceptualization, methodology, investigation, formal analysis, validation, and writing – original draft. XW: methodology and writing – review and editing. DL: supervision, project administration, writing – review and editing, and funding acquisition; SD: writing – review and editing; YX: data curation and resources. PW: data curation and resources. ZW: data curation. All authors contributed to the article and approved the submitted version.

Acknowledgments

We would like to thank our colleagues in Marine Biogeochemistry Laboratory for their assistance in data collection and analysis. We gratefully acknowledge the financial support of the Guangxi Education Department (No. 2022KY0411), Beibu Gulf Ocean Development Research Center (BHZKY202007), National Natural Science Foundation of China (No. 41966002), Marine Science Guangxi First-Class Subject, Beibu Gulf University (DRC006).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abdullah, A. Y. M., Masrur, A., Adnan, M. S. G., Baky, M. A. A., Hassan, Q. K., and Dewan, A. (2019). Spatio-temporal patterns of land use/land cover change in the heterogeneous coastal region of Bangladesh between 1990 and 2017. *Remote Sens* 11 (7), 790. doi: 10.3390/rs11070790

Alves, F. L., Sousa, L. P., Almodovar, M., Phillips, M. R., Alves, F. L., Sousa, L. P., et al. (2013). Integrated coastal zone management (ICZM): a review of progress in Portuguese implementation. *Reg. Environ. Change.* 13 (5), 1031–1042. doi: 10.1007/s10113-012-0398-y

Banerjee, S., Kumar, A., Maiti, S. K., and Chowdhury, A. (2016). Seasonal variation in heavy metal contaminations in water and sediments of jamshedpur stretch of subarnarekha river, India. *Environ. Earth Sci.* 75 (3), 1–12. doi: 10.1007/s12665-015-4990-6

Beatley, T., Brower, D., and Schwab, A. K. (2002). *An introduction to coastal zone management* (Washington: Island Press).

Bera, S., Das, A., and Mazumder, T. (2019). A multi-objective framework for multidimensional vulnerability assessment–case of a coastal district of West Bengal, India. *J. Environ. Manage* 249, 109411. doi: 10.1016/j.jenvman.2019.109411

Bi, M., Xie, G., and Yao, C. (2020). Ecological security assessment based on the renewable ecological footprint in the guangdong-Hong Kong-Macao greater bay area. *China. Ecol. Indic.* 116, 106432. doi: 10.1016/j.ecolind.2020.106432

Bryan-Brown, D. N., Connolly, R. M., Richards, D. R., Adame, F., Friess, D. A., and and Brown, C. J. (2020). Global trends in mangrove forest fragmentation. *Sci. Rep.* 10 (1), 1–8. doi: 10.1038/s41598-020-63880-1

Chen, M. H., Chen, F., Tang, C. J., Lu, Y., and Feng, Y. X. (2022). Integration of DPSIR framework and TOPSIS model reveals insight into the coastal zone ecosystem health. *Ocean Coast. Manage.* 226, 106285. doi: 10.1016/j.ocecoaman.2022.106285

Cheng, H., Zhu, L., and Meng, J. (2022). Fuzzy evaluation of the ecological security of land resources in mainland China based on the pressure-State-Response framework. *Sci. Total Environ.* 804, 150053. doi: 10.1016/j.scitotenv.2021.150053

Chen, J., Wei, F., Zheng, C., Wu, Y., Adriano, D. C., Chen, J., et al. (1991). Background concentrations of elements in soils of China. *Water. Air. Soil Poll.* 57 (1), 699–712. doi: 10.1007/BF00282934

Ersha, D., Wen, J. H., and Gan, L. C. (2017). Evaluation of regional ecological vulnerability of coastal zone in dongshan county based on VSD model. *Mar. Environ. Sci.* 36 (2), 296–302. doi: 10.13634/j.cnki.mes.2017.02.022

Fabbri, K. P. (1998). A methodology for supporting decision making in integrated coastal zone management. *Ocean. Coast. Manage.* 39 (1-2), 51–62. doi: 10.1016/S0964-5691(98)00013-1

Gao, L., Ning, J., Bao, W. L. T. Y., Yan, A., and Yin, Q. R. (2022). A study on the marine ecological security assessment of guangdong-Hong Kong-Macao great bay area. *Mar. pollut. Bull.* 176, 113416. doi: 10.1016/j.marpolbul.2022.113416

Gu, Y. G., Lin, Q., Yu, Z. L., Wang, X. N., Ke, C. L., and Ning, J. J. (2015). Speciation and risk of heavy metals in sediments and human health implications of heavy metals in edible nekton in beibu gulf, China: A case study of qinzhou bay. *Mar. pollut. Bull.* 101 (2), 852–859. doi: 10.1016/j.marpolbul.2015.11.019

He, Y., and Kuang, Y. (2020). Evaluation and analysis of ecological security of coastal zone in huizhou of guangdong-Hong Kong-Macao greater bay area based on DPSIR model. *Environ. pollut. Prev.* 42 (3), 362–368.

Jana, S. (2020). Micro-level coastal vulnerability assessment in relation to post-aila landscape alteration at the fragile coastal stretch of the sagar island, India. *Reg. Stud. Mar. Sci.* 33, 100908. doi: 10.1016/j.rsma.2019.100908

Jiang, Y. H., and Fang, L. J. (2009). New ideas for improving china's coastal zone management legislation, drawing on the experi-ence of the united states. *China Oceans Law Rev.* 2, 84–90.

Jian, W., Yuhao, Z., and Tian, Y. (2020). Evolution of typhoon disasters characteristics and non-structural disaster avoidance measures in the China coastal main functional area. *Int. Disast. Risk. Re.* 46, 101490. doi: 10.1016/j.ijdrr.2020.101490

Jian, W., Yuhao, Z., Tian, Y., Bikai, C., Portman, M. E., Esteves, L. S., et al. (2012). Improving integration for integrated coastal zone management: An eight country study. *Sci. Total. Environ.* 439, 194–201. doi: 10.1016/j.scitotenv.2012.09.016

Jiao, N. Z., Chen, D. K., Luo, Y. M., Huang, X. P., Zhang, R., Zhang, H. B., et al. (2015). Climate change and anthropogenic impacts on marine ecosystems and countermeasures in China. *Adv. Clim. Change Res.* 6 (2), 118–125. doi: 10.1016/j.accre.2015.09.010

Liang, J., and Li, Y. (2020). Resilience and sustainable development goals based social-ecological indicators and assessment of coastal urban areas–—A case study of dapeng new district, shenzhen, China. *Watershed. Ecol. Environ.* 2, 6–15. doi: 10.1016/j.wsee.2020.06.001

Lin, J., Lin, M., Chen, W., Zhang, A., Qi, X., and Hou, H. (2021). Ecological risks of geological disasters and the patterns of the urban agglomeration in the fujian delta region. *Ecol. Indic.* 125, 107475. doi: 10.1016/j.ecolind.2021.107475

Liu, L., Wang, H., and Yue, Q. (2020). China's coastal wetlands: Ecological challenges, restoration, and management suggestions. *Reg. Stud. Mar. Sci.* 37, 101337. doi: 10.1016/j.rsma.2020.101337

Li, Q., and Yan, J. (2021). An evaluation of ecological security of coastal zone of sanya with DPSIR model. *Trans. Oceanol Limnol* 4, 147–152.

Lu, X., Yao, S., Fu, G., Lv, X., Mao, Y., Lu, X., et al. (2019). Dynamic simulation test of a model of ecological system security for a coastal tourist city. *J. Destin. Mark. Manage.* 13, 73–82. doi: 10.1016/j.jdmm.2019.05.004

Mokhtar, M. B., and Aziz, S. A. B. A. G. (2003). Integrated coastal zone management using the ecosystems approach, some perspectives in Malaysia. *Ocean. Coast. Manage.* 46 (5), 407–419. doi: 10.1016/S0964-5691(03)00015-2

Morsy, A., Ebeid, M., Soliman, A., Halim, A. A., Ali, A. E., and Fahmy, M. (2022). Evaluation of the water quality and the eutrophication risk in Mediterranean sea area: A case study of the port said harbour, Egypt. *Environ. Chall.* 7, 100484. doi: 10.1016/j.envc.2022.100484

Rajakumari, S., Minnu, A., and Sarunjith, K. J. (2022). Determination of vulnerable zones along brahmapur coast, odisha using AHP and GIS with validation against multiple cyclones. *Environ. Monit. Assess.* 194 (4), 1–19. doi: 10.1007/s10661-022-09886-w

Shipman, B., and Stojanovic, T. (2007). Facts, fictions, and failures of integrated coastal zone management in Europe. *Coast. Manage.* 35 (2-3), 375–398. doi: 10.1080/08920750601169659

Su, L., Fan, J., and Fu, L. (2020). Exploration of smart city construction under new urbanization: A case study of jinzhou-huludao coastal area. *Sustain. Comput-Infor* 27, 100403. doi: 10.1016/j.suscom.2020.100403

The People's Republic of China (2021). *Outline of the 14th five-year plan for national economic and social development of the people's republic of China and the vision for 2035.* Available at: http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.

Wang, Y. (2003). "Coastal management in China," in *Ocean management in global change* (CRC Press), 469. doi: 10.1201/9781482286830-25

Wei, C., Guo, Z., Wu, J., and Ye, S. (2014). Constructing an assessment indices system to analyze integrated regional carrying capacity in the coastal zones–a case in nantong. *Ocean. Coast. Manage.* 93, 51–59. doi: 10.1016/j.ocecoaman.2014.02.009

Westmacott, S. (2001). Developing decision support systems for integrated coastal management in the tropics: is the ICM decision-making environment too complex for the development of a useable and useful DSS. *J. Environ. Manage.* 62 (1), 55–74. doi: 10.1006/jema.2001.0420

Wu, X. Q., Gao, M., Wang, D., Wang, Y., Lu, Q. S., and Zhang, Z. D. (2012). Framework and practice of integrated coastal zone management in Shandong province, China. *Ocean. Coast. Manage.* 69, 58–67. doi: 10.1016/j.ocecoaman.2012.07.030

Xiao, L., Shan, G., Tianyu, Z., and Guimei, L. (2018). Researching progress and application status of eutrophication evaluation method of seawater. *Adv. Earth. Sci.* 33 (4), 373.

Xu, C., Pu, L., Zhu, M., Li, J., Chen, X., Wang, X., et al. (2016). Ecological security and ecosystem services in response to land use change in the coastal area of jiangsu, China. *Sustain.* 8 (8), 816. doi: 10.3390/su8080816

Xu, Y., Zhang, T., and Zhou, J. (2019). Historical occurrence of algal blooms in the northern beibu gulf of China and implications for future trends. *Front. Microbiol.* 10, 451. doi: 10.3389/fmicb.2019.00451

Yanes, A., Botero, C. M., Arrizabalaga, M., and Vásquez, J. G. (2019). Methodological proposal for ecological risk assessment of the coastal zone of antioquia, Colombia. *Ecol. Eng.* 130, 242–251. doi: 10.1016/j.ecoleng.2017.12.010

Yang, X., Duan, J., Wang, L., Li, W., Guan, J., and Beecham, S. (2015). Heavy metal pollution and health risk assessment in the wei river in China. *Environ. Monit. Assess.* 187 (3), 1–11. doi: 10.1007/s10661-014-4202-y

Yang, X. E., Wu, X., Hao, H. L., and He, Z. L. (2008). Mechanisms and assessment of water eutrophication. *J. Zhejiang. University. Sci.* 9 (3), 197–209. doi: 10.1631/jzus.B0710626

Ye, Y. H., and Yaoqiu, K. (2020). Ecological security evaluation analysis of coastal zone in huizhou, guangdong, Hong Kong and Macao bay area based on the driver-pressure-state-impact-response mode. *Environ. Poll. Prev.* 42 (3), 362–368.

Yong, M. L. (2016). Ecological and environmental issues in the sustainable development of china's coastal zone and the development of coastal science. *P. Chinese. Acad. Sci.* 31 (10), 1133–1142.

Zhang, K., and Wen, Z. (2008). Review and challenges of policies of environmental protection and sustainable development in China. *J. Environ. Manage.* 88 (4), 1249–1261. doi: 10.1016/j.jenvman.2007.06.019

Zong, S., Hu, Y., Zhang, Y., and Wang, W. (2021). Identification of land use conflicts in china's coastal zones: From the perspective of ecological security. *Ocean. Coast. Manage.* 213, 105841. doi: 10.1016/j.ocecoaman.2021.105841