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Construction and Application of a Coastline Ecological Index: A Case Study of Fujian Province, China

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Abstract: Coastlines are at the forefront of interactions between the ocean and land, and have important ecological significance. Remote sensing technology, with its advantages in obtaining large-scale and multiscale data, has become an important aid in constructing comprehensive ecological environment indicators. Based on the Landsat TM/ETM+/OLI/TIRS data sources and remote sensing technology, a comprehensive index to evaluate the ecological health of the coastline, the coastline ecological index (CEI), was proposed, and the mainland coastline ecology of Fujian Province from 1992 to 2022 was evaluated. Case studies show that the ecological health of Fujian Province's coastline, as measured by CEI values, decreased from 98.1 in 1992 to 16.6 in 2007 and then gradually increased to 37.6 in 2022, demonstrating a trend of initial decline followed by a rise. During the study period, the total length of Fujian Province's coastline decreased from 3373.1 km in 1992 to 2985.5 km in 2012 and then increased to 3123.4 km in 2022, accompanied by the transformation of a large number of natural coastlines into artificial coastlines. The study found that before 2007, China carried out unreasonable development of its coastline for economic development, which caused natural coastline damage and a decline in the CEI value. Since 2012, China has combined environmental protection with economic development. Policy adjustments have reduced coastline damage and increased restoration efforts, and the CEI value has risen. The CEI constructed in this study has good adaptability for application in Fujian Province, and changes in CEI values can better reflect changes in the ecological degree of the coastline in Fujian Province. Following a case study and detailed discussion, we believe that CEI has universal applicability for the comprehensive evaluation of coastline ecology.

Keywords: index system; coastline transformation; remote sensing; ecological health

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1. Introduction

The coastal zone is a typical ecological ecotone and ecologically fragile zone. It is the area with the most active human economic, social, and environmental activities in the world [1,2]. It is extremely sensitive to external disturbances, especially human activities [3]. Coastlines are at the forefront of the interactions between the ocean and land in coastal zones. They are a special, nonrenewable resource that combines water and soil [4]. The temporal and spatial changes in coastlines reflect the interplay between local environmental protection, economic development, and policy orientation [5]. Coastal zones are highly dependent on the safety and stability of coastline ecology.

To understand the current status of ecosystems and predict future change trends, we usually use ecological indicators that are simple, quantifiable, and easy to interpret. Ecological indicators are usually simplified and comprehensive expressions of various complex ecosystem information [6]. With the innovation of geographic information systems and remote sensing technology [7], domestic and foreign scholars have conducted many studies on the construction of ecological indicators and proposed a large number of new indicators and methods to address large-scale ecological environmental changes. However, most of the previously proposed formula methods involve the detection of a single ecological factor or a single aspect of ecological conditions. The leaf area index (LAI) [8], normalized water index (NDWI) [9], normalized vegetation index (NDVI) [10], and land surface temperature (LST) [11] cannot reflect the overall ecological status of a certain area. With changes in actual needs, some scholars have begun to propose the concept of comprehensive indicators, which comprehensively consider the influence of various factors, such as the remote sensing ecological index (RSEI) proposed by Xu, H. Q. et al. [12] based on remote sensing data; additionally, Wanda, D. K. et al. [13] proposed a global ecosystem stability framework assessment system based on remote sensing, and Mohammad, K. F. et al. [14] used the land surface ecological state composition index (LSESCI) developed from the RSEI to conduct an ecological evaluation of the Sungun copper mine in Iran and believed that the performance of the LSESCI was greater than that of the RSEI. In recent years, many scholars have also taken the coastal zone ecosystems as the main research area and constructed comprehensive indexes to evaluate the vulnerability of the coastal zone; for example, as Ai, B. et al. [15] calculated and evaluated the coastal exposure index (CEI) of Jiaozhou Bay in China and analyzed the vulnerability of the bay. Bagdanavičiūtė, Ingrida, B. et al. [16] used the Environmental Sensitivity Index (ESI) to analyze the exposure and vulnerability of the coastal areas of Lithuania.

At present, the study areas for comprehensive ecological indexes are mostly within administrative regions [12,17], river basins [18,19], coastal zones [15,16] and geographical ecological units [20]. There are relatively few comprehensive ecological evaluation indexes with coastlines as the main research area.

Among many studies that use coastlines as study areas, research has focused mainly on changes in coastline length and sea–land area [21–23], the transfer of coastline utilization methods [24–26] and the spatiotemporal dynamics of coastline fractal dimensions [27–29]. Then, they focus on the deep driving forces of coastline spatial and temporal changes [21,30], the prediction of coastline changes [31,32], public perception research [33] and the provision of policy suggestions for local governments [34]. Dionysios, A. et al. [35] found in their review that recent studies on coastline risks are increasing, and Landsat data are widely used due to their easy accessibility and long time series. Munshi, K. R. et al. [36] found in their study that the United States has made the greatest contribution to the study of coastline evolution.

Another part of the research focuses on coastline risk research. Parthasarathy, K. S. S. et al. [37] reviewed the research progress of shoreline changes and the coastal vulnerability index (CVI). Jahangir, J. et al. [38] studied the ecological risks of artificial facilities to the coastline, and Mahendra, R. S. et al. [39] studied the risks of flooding in the coastal areas of Andhra Pradesh. There are few studies that examine the ecological environment of the coastline as a whole.

Fujian Province is located in southern China, north of the Tropic of Cancer. Fujian's land area ranges from 25°09′ to 28°19′ N, 115°50′ to 118°42′ E, bordering Zhejiang Province to the north, Guangdong Province to the south, Jiangxi Province to the west, and facing Taiwan Province across the strait (Figure 1). The total land area is 124,000 square kilometers. As of 2022, the permanent population of Fujian Province is 41.88 million [40]. Fujian's coastline is a zigzag, with many bays and peninsulas in the main body. The straight coastline length is 535 km, and the curve length is more than 3000 km, accounting for approximately 18.3% of the total length of China's coastline, ranking second among all provinces in China [41]. Fujian Province is an important ecological barrier in southern China. Fujian Province's forest coverage rate has reached 65.12%, ranking first in the country for 45 consecutive years [42], The proportion of days with excellent air quality in cities in Fujian Province is 98.5%, and the proportion of excellent water quality in major river basins reaches 99%. The eco-civilization index ranks first in the country [43]. Therefore, taking Fujian Province, which has a complex coastline and diverse coastline ecological environment, as an example, we can demonstrate that it is very important to construct a coastline ecological index system, as well as to verify and promote the index.

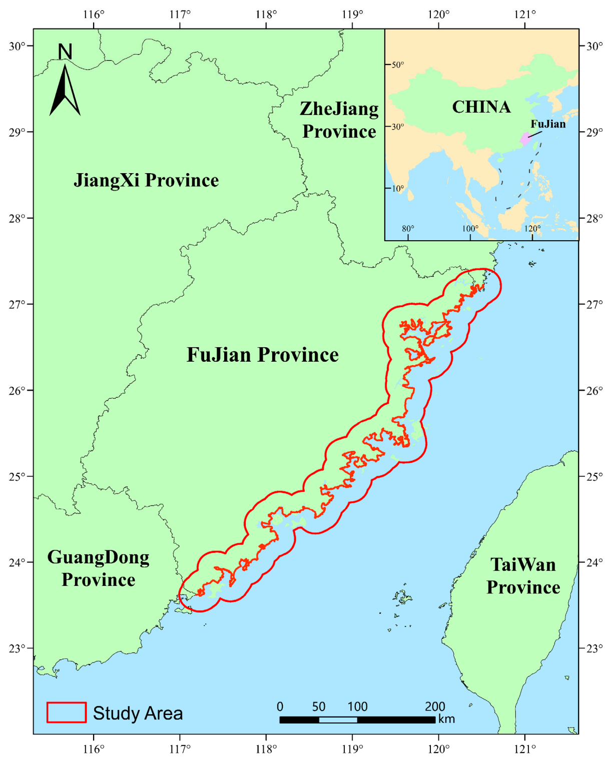


Figure 1. Study area.

Based on the above research progress, it is believed that the current research on coastline changes has achieved certain results, but there are gaps in the research on the coastline ecological environment; at the same time, there is also a lack of research on the comprehensive ecological index of the coastline. To fill this gap, this study aimed to delve more deeply into the ecological impacts reflected in shoreline-related changes to address the apparent lack of research in this area. This study referred to the existing comprehensive index system to construct a universal comprehensive evaluation index system for coastline ecology. Remote sensing image data from China's Fujian Province were used to extract the mainland coastline for a case analysis to evaluate the coastline ecology of China's Fujian Province from 1992 to 2022. The index evaluation framework and results constructed in this study can be used as a reference for relevant management agencies and researchers.

2. Data and Methods

2.1. Coastline Ecological Index

This study is based on the framework of the island ecological index in the "Island Ecological Index Evaluation Method" [44,45] and refers to ideas from the United Nations Sustainable Development Report (SDGR) [46], Ocean Health Index (OHI) [47], Coastal Governance Index (CGI) [48] and other indexes. Appropriate indicators were selected to evaluate the ecological status of the coastline of Fujian Province.

Since the primary objective in developing a coastline ecological evaluation index system is to assess the ecological health of a region's coastline, the chosen indicators must accurately reflect the coastline's attributes and characteristics. They should comprehensively measure the ecological health of the coastline at a specific point in time. Therefore, after considering the scientific significance, representativeness, independence, relevance to the topic, and universality of the indicators, the current indicators were selected.

The evaluation index system consists of three first-level indicators and six second-level indicators. The primary indicators include the ecological environment, ecological pressure, and dynamic changes. The secondary indicators include the natural coastline retention rate (*NCR*), coastal vegetation rate (*CVR*), water quality (*WQ*), index of coastline type diversity (*ICTD*), coastline artificial index (*CAI*) and coastline dynamics degree (*DD*) (Table 1).

Table 1. Coastline ecological index indicator system.

Comprehensive Indicators	Primary Indicators	Secondary Indicators	Indicator Properties
Coastline Ecological Index	Ecology and environment	Natural coastline retention rate Coastal vegetation rate Water quality	Positive Positive Negative
	Ecological pressure	Index of Coastline type diversity Coastline artificial index	Negative Negative
	Dynamic changes	Coastline dynamics degree	Negative

In summary, this study constructed a comprehensive indicator system that can reflect the comprehensive ecological status of the coastline in a certain area by selecting indicators from different aspects. Among them, *NCR*, *CVR* and *WQ* evaluate the ecological health of the coastline from aspects of the integrity and originality of the natural ecosystem; *ICTD* and *CAI* evaluate the impact and diversity of the coastline ecosystem under human activities; and *DD* evaluates and quantifies the changes to the coastline that are mainly dominated by human activities.

This study also references the index aggregation system from the Capacity Index of the Sustainable Coastal Development Report for Countries Along the Maritime Silk Road (CISCDR) and employs the constant elasticity of substitution (CES) function method to aggregate the sub-indicators. Analysis suggests that the sub-indicators within this index are highly substitutable. Also, to ensure that the index system reflects the overall ecological state of the coastline rather than emphasizing the region's defects and shortcomings, the equal-weight linear aggregation scenario of the CES function is chosen for sub-indicator aggregation. The three primary indicators in the index system have equal weights, and the secondary indicators of each first-level indicator also have equal weights.

The calculation formula for the coastline ecological index (CEI) is as follows:

$$\mathrm{CEI} = \sum_{i=1}^{6} p_i A_i \times 100, \tag{1}$$

where CEI is the coastline ecological index, *Ai* is the normalized value of each subindicator, and *pi* is the weight corresponding to *Ai*.

This study used the maximum and minimum methods to normalize the data [49]. The specific formula is as follows:

$$A_1 = \frac{X_{max} - X_i}{X_{max} - X_{min}}, \tag{2}$$

$$A_2 = \frac{X_i - X_{min}}{X_{max} - X_{min}}, \tag{3}$$

where A_1 is the normalized value of the negative indicator, A_2 is the normalized value of the positive indicator, X_i is the indicator data of the *i*-th period, and X_{max} and X_{min} are the maximum and minimum values of the indicator, respectively.

2.1.1. Natural Coastline Retention Rate

The "National Marine Functional Zoning (2011–2020)" was the first report to propose the natural coastline retention rate as a control indicator to reserve strategic resources for the sustainable development of the ocean [50]. To reflect the level of sustainable development capability of coastlines, the natural coastline retention rate [44] is selected to describe the changes in the proportion of the natural coastline. The specific formula is as follows:

$$NCR = {L_n}\Big/{L} \times 100\%, \tag{4}$$

where NCR is the natural coastline retention rate, L is the total length of the coastline, and L_n is the length of the natural coastline. Both L and L_n are derived from the coastline extracted by MNDWI.

The greater the proportion of natural coastlines, the greater the level of coastline sustainability, and the greater the overall ecological level of the coastline. The natural coastline retention rate is a positive indicator.

2.1.2. Coastal Vegetation Rate

Paul, T. A. et al. [51] believe that vegetation biological barriers in coastal zones are effective coastline protection measures and can solve ecosystem problems such as coastline erosion to a certain extent. The coastal vegetation rate reflects the ecological quality and coastal protection measures of the landward side of the coastline.

Article 19 of the "Fujian Province Coastal Zone Protection and Utilization Management Regulations" stipulates that the building setback line of buildings in unbuilt areas of the coastal zone is 200 m, based on the coastline [52]. The study uses 200 m as the calculation boundary for landward vegetation coverage along the coastline. The specific formula [44] for the coastal vegetation rate is as follows:

$$CVR = {N_V}\Big/{N} \times 100\%, \tag{5}$$

where CVR is the coastal vegetation rate, N is the total area of the coastal zone, and N_v is the vegetation coverage area, which is calculated using the NDVI interpreted from Landsat remote sensing images.

NDVI is an index proposed by Kriegler, F et al. [53] to describe vegetation distribution. The specific calculation formula is as follows:

$$\mathrm{NDVI} = \frac{NIR - RED}{NIR + RED}, \tag{6}$$

where NDVI is the normalized difference vegetation index, and NIR and RED are measurements of near infrared and red from satellite sensors.

Since the coastal vegetation biological barrier is an effective coastline protection measure and is beneficial to the ecological health of the coastline, CVR is a positive indicator.

2.1.3. Water Quality

The quality of offshore seawater reflects the ecological excellence of the seaward side of the coastline. Chen, J. et al. [54] reported that the concentration of chlorophyll a is negatively correlated with major water quality indicators and suggested that the concentration of chlorophyll a can reflect water quality. Therefore, the chlorophyll a concentration is used to characterize offshore water quality. The specific formula is as follows:

$$WQ = \sum_1^{12} \frac{\sum_i^n A_i}{n} \Big/ 12, \tag{7}$$

where WQ is the water quality index; n is the number of offshore water quality monitoring points in the study area; and A_i is the chlorophyll a concentration of the i-th water quality monitoring point [55]. The original data were collected on a monthly basis, but they were ultimately averaged annually. WQ is a negative indicator.

2.1.4. Index of Coastline Type Diversity

The manner and intensity of coastline utilization reflects the nature and processes of human activities that interfere with the natural ecosystem of coastlines [56]. The index of coastline type diversity is constructed with reference to the index of land use type diversity [3] and landscape diversity index to describe the diversity of coastline use patterns. The specific formula [3] is as follows:

$$ICTD = 1 - \frac{\sum_i^n L_i^2}{\left(\sum_i^n L_i\right)^2}, \quad (8)$$

where $ICTD$ is the index of coastline type diversity, n is the number of coastline types, and L_i is the corresponding length of the i-th type of coastline. L_i comes from the coastline extracted via MNDWI.

The range of $ICTD$ is between 0 and 1. The closer it is to 0, the more monotonous the coastline type is, and the more inclined it is to a planned development model. The closer it is to 1, the more complex the coastline utilization type is, and the more inclined it is to disorderly development and utilization. It is generally believed that more planned development of coastlines is consistent with ecological health concepts. The shoreline type diversity index value is a negative indicator.

2.1.5. Coastline Artificial Index

To accurately quantify the ecological pressure on coastlines caused by different types of human sea-use activities, a coastline artificial index was constructed with reference to the comprehensive index of coastline utilization to quantitatively evaluate the ecological impact of different types of human sea-use activities on the coastline [3,57]. First, according to the intensity of human activities, that is, the degree of change in the type and location of the original coastline, different human intensity indices are assigned to each type of coastline [57]. Table 2 shows the specific values.

Table 2. Human intensity indices of various types of coastlines.

Coastline Type	Natural Coastline					Artificial Coastline		
	Bedrock Coastline	Sandy Coastline	Biological Coastline	Muddy Coastline	Natural Estuary	Mariculture Coastline	Artificial Construction Coastline	Artificial Estuary
Index	1	1	1	1	1	2	3	3

The Coastline Artificial Index is calculated based on the human intensity index. The specific formula [3,57,58] is as follows:

$$CAI = \sum_{i=1}^n (A_i \times C_i) \times 100, \quad (9)$$

where CAI is the coastline artificial index; A_i is the human intensity index corresponding to the i-th type of coastline; and C_i is the percentage of the length of the i-th type of coastline. C_i comes from the coastline extracted via MNDWI.

According to the definition of the human intensity index, the value of shoreline artificial utilization in this study ranged from 100 to 300. The greater the degree of artificial utilization of the coastline, the greater the degree of human disturbance to the coastline, and the more difficult it will be to restore the coastline to its natural state. Therefore, the lower the CAI is, that is, the less affected it is by human activities, the healthier the coastline ecology is. Therefore, the CAI calculated based on the data of each period is a negative indicator.

2.1.6. Coastline Dynamics Degree

Dynamic changes in the time scale of coastlines also have a profound impact on their own ecological security. To analyze the instability of the ecological environment caused by dynamic changes in the coastline, the coastline dynamic degree (*DD*) index was constructed. The specific formula [3] is as follows:

$$DD = \frac{\sum_i^n |V_i|}{n}, \tag{10}$$

where *DD* is the coastline dynamic degree; V_i is the seaward or landward change rate of the coastline on the *i*-th section line; and *n* is the number of transection lines.

Coastline changes can be analyzed using the baseline method. The baseline method is a method for analyzing changes in coastlines at different time phases. And the baseline method has been integrated into the Digital Shoreline Analysis System (DSAS), an ArcGIS extension developed by the National Shoreline Assessment Project implemented by the USGS. To date, DSAS has been widely used in the analysis and prediction of the coastlines of lakes [59], oceans [58,60,61] and other water bodies.

This study uses DSAS to calculate the coastline dynamics degree. First, the data are integrated through the seven-period coastline extraction results to establish a buffer zone towards the land. After adjustment, the coastline baseline can be established. One end of the baseline is selected as the starting point, and transection lines with a length of 2500 m and an interval of 300 m are generated towards the ocean. Each transection line is required to intersect with the coastline of each period. Finally, calculations of various change rates are completed based on the intersection of the generated section line with the coastline. Since the analysis object of the coastline dynamic degree is a period, the dynamic degree at each time point is calculated by taking the average value of the dynamic degree of the two periods before and after.

The degree of dynamics is closely related to the stability of the coastline and reflects the resilience of the coastline ecosystem. The greater the coastline dynamics, the more unstable the coastline will be, and the more severe the expansion or erosion will be. A long-term stable coastline ecosystem can bring greater ecological benefits; that is, a coastline with low coastline dynamics has a better ecological degree. As a result, the coastline dynamic degree can be used as an indicator of coastline ecology, and it is a negative indicator.

2.2. Data Sources

The remote sensing image data used in the study come from the United States Geological Survey (USGS). This dataset combines data and cloud cover data and uses Landsat 5 TM C2 L1, Landsat 7 ETM+ C2 L1, and Landsat 8/9 OLI/TIRS C2 L1 data products from 1992, 1997, 2002, 2007, 2012, 2017, and 2022 [62]. The specific parameters of the remote sensing image data are shown in Table 3. Since Fujian Province in China has heavy rains in spring and frequent typhoons in summer, after comparison, the remote sensing image data were selected to give priority to the data from September to December, when there is less cloud cover. Images with the same strip number are selected when the overall cloud cover is less than 15%, the main study area is cloud-free, and the study area can be completely covered. The data from each remote sensing image are preprocessed after downloading. The process includes geometric correction, radiometric calibration, atmospheric correction, image enhancement, image mosaicking and cropping. Among them, the Landsat7 data used in 2007 and 2012 had missing strips. Before other preprocessing steps, the Landsat_gapfill plug-in is used to fill and repair the missing strips.

Table 3. Remote sensing image data parameter information for the study area.

Year	Remote Sensing Sensor	Number of Bands	Projected Coordinate System	Strip Serial Number
1992	Landsat5 TM	7	UTM zone 51 N	118041, 118042, 118043, 119041, 119042, 119043, 120043, 120044
1997	Landsat5 TM	7	UTM zone 51 N	
2002	Landsat5 TM	7	UTM zone 51 N	
2007	Landsat7 ETM+	8	UTM zone 50 N	
2012	Landsat7 ETM+	8	UTM zone 50 N	
2017	Landsat8 OLI/TIRS	9 + 2	UTM zone 51 N	
2022	Landsat9 OLI/TIRS	9 + 2	UTM zone 51 N	

The data used in the calculation of sub-indicators include chlorophyll data for water quality calculation. The chlorophyll data [55] were downloaded from NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC).

The data used for accuracy verification include SPOT series satellite data, Sentinel-2 satellite data and Google Earth Pro 7.3.6 software. SPOT series satellite data were downloaded from The National Centre for Space Studies (CNES) in France. Sentinel-2 satellite data were downloaded from Copernicus from The European Space Agency (ESA). Google Earth Pro 7.3.6 software was downloaded from the Google Earth official website.

2.3. Coastline Extraction and Verification

2.3.1. Coastline Extraction

Due to the high degree of development of the coastal zone in Fujian Province and the large number of coastal buildings, the use of the traditional normalized difference water index (NDWI) to extract waterside lines will produce considerable noise, and the extraction effect will be poor. ENVI5.6 software was selected for data processing. Therefore, the modified normalized difference water index (MNDWI) was selected to extract the coastline [63]. The MNDWI can quickly and accurately extract waterside lines while reducing the impact of buildings on the accuracy of the results. The specific formula is as follows:

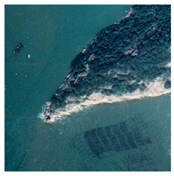
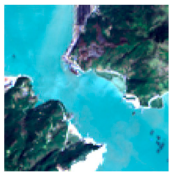
$$\mathrm{MNDWI} = \frac{Green - MIR}{Green + MIR}, \tag{11}$$

where *Green* is the green band corresponding to band 2 of the TM/ETM+ sensor and band 3 of the OLI sensor, and *MIR* is the mid-infrared band corresponding to band 5 of the TM/+ETM sensor and band 6 of the OLI sensor.

The decision tree classification method is used to binarily classify the MNDWI results, and 0 is selected as the classification threshold [64]. The ArcGIS 10.8 software was used to further process the files after preliminary extraction. After small-class processing, vectorization, smoothing, and manual elimination of islands and land water bodies, obvious errors were manually corrected to obtain the instantaneous water edge of the mainland coastline.

According to the provisions of the "Technical Regulations for Coastal Zone Survey" and its Appendix A-1, issued by the 908 Special Office of the State Oceanic Administration [65], certain modifications and additions were made based on the actual situation of the coastline of Fujian Province. For example, Fujian Province in China has good ecology, so the biological coastline is classified as an independent category; at the same time, Fujian Province is a traditional mariculture area, so mariculture is also classified as an independent category. The coastline of Fujian Province is divided into two parts: artificial coastline and natural coastline. Artificial coastlines include mariculture coastlines, artificial construction coastlines and artificial estuary coastlines. Natural coastlines include bedrock coastlines, sandy coastlines, muddy coastlines, biological coastlines and natural estuary coastlines. The interpretation of the data and the corresponding classification principles are shown in Table 4. Instantaneous waterside lines were classified with reference to interpretation signs.

Table 4. Coastline interpretation signs and classification principles of Fujian Province.

Coastline Type	Utilization Method	Established Principles	Interpretation Signs
Natural coastline	bedrock coastlines	Most of them are located in the areas between headlands and bays. The coastline has complex curves and slender bright edges.	
	sandy coastlines	Mostly in the seaward area. The coastline grows into an arc, showing a bright white strip, and the width is related to the position of the tide.	
	biological coastlines	Most of them are distributed in slow currents such as estuaries and inner bays. They appear red in the false color image and extend towards the sea.	
	muddy coastlines	Most of them are distributed in slow flow areas and the seaside side of plains, showing different dark colors depending on the substrate.	
	natural estuary coastlines	If there is no artificial structure as a boundary where the river flows into the sea, the location at which the river suddenly widens will be used as the shoreline location.	
Artificial coastline	mariculture coastlines	Most of them are distributed near the muddy coastline or on the seaside plain, showing regular square sheets.	
	artificial construction coastlines	Artificially constructed seawater isolation facilities and reclamation project sites are characterized by sharp edges and straight boundaries in the image.	
	artificial estuary coastlines	The first man-made structure encountered in the estuary area from the sea to the river serves as the estuary coastline.	

Since the coastline is the dividing line between seawater and land, formed by the average high tide over many years and affected by tidal effects, the instantaneous waterline captured by satellites passing through at a certain moment is not completely equivalent to the coastline. Therefore, the trigonometric function method is used to perform tidal correction on gently sloping coastlines (sandy coastlines, biological coastlines, and muddy coastlines) [66]. The specific formula is as follows:

$$L = \frac{H - h_2}{(h_2 - h_1)/\Delta L} \tag{12}$$

where h_1 and h_2 are the tide heights when the remote sensing images of two scenes at different imaging times at the same point are in phase ($h_1 < h_2$); ΔL is the horizontal distance between the water edges of the two scene images; and H is the multiyear average spring tide height of the point. L is the horizontal distance from the real coastline to the position corresponding to the waterline in the h_2 remote sensing image.

Based on the above tidal correction principle, the actual coastline can be obtained by moving the instantaneous waterline of the gently sloping coastline of Fujian Province towards the land by a distance L. Since the slopes of the bedrock coastline and artificial construction coastline are steeper near the shore, the water edge is less affected by the tide, so no correction is made. In actual practice, based on the distinction of coastline types, remote sensing images with different tidal positions at various time periods are used to select some typical coastlines for calculating the L value. The coastline position is then manually corrected according to the range of these calculation results.

2.3.2. Coastline Accuracy Verification

Landsat satellite remote sensing data were utilized in this study due to their provision of over 50 years of stable, long-term remote sensing image series. Nevertheless, Landsat data have limitations, such as low resolution and inconsistent data quality [67], which may impact the accuracy of coastline extraction results. To address this issue, we used high-resolution image data from the SPOT series satellites and Sentinel-2 satellites to verify the accuracy of the coastline extraction results. Specifically, SPOT series satellite data were used to verify the extraction results for the years 1992, 1997, 2002, 2007, and 2012, while Sentinel-2 satellite data were used to verify the extraction results for the years 2017 and 2022.

In areas that are more difficult to identify, confirmation should be carried out using high-precision aerial imagery in conjunction with the timeline function of Google Earth.

Due to the large amount of data, this study verifies the accuracy of coastline extraction using the random point method. This involves randomly generating 200 control points within each interpretation result area for position and type checks. If the error is within 1 pixel, the extraction is considered to meet the accuracy requirements; otherwise, it is deemed not to meet the requirements.

After manual inspection and statistical analysis, the specific accuracy inspection results are shown in Table 5. The positional accuracy of the coastline extracted from the seven phases of remote sensing images from 1992 to 2022 ranges from 90.5% to 96.5%, while the type accuracy ranges from 97.5% to 99.0%. These extraction accuracies meet the research requirements. It should be noted that the Landsat 7 remote sensing images used for the 2007 and 2012 data have significant strip-missing issues, resulting in lower extraction accuracy compared to other years.

Table 5. Coastline extraction accuracy check.

Year	Position Deviation Points	Type Error Point	Position Accuracy/%	Type Accuracy/%
1992	7	4	96.5	98.0
1997	12	3	94.0	98.5
2002	9	3	95.5	98.5
2007	19	5	90.5	97.5
2012	16	2	92.0	99.0
2017	7	4	96.5	98.0
2022	8	2	96.0	99.0

3. Results

3.1. Coastline Change Dynamics

The extraction results of the Fujian Province coastline data for seven periods from 1992 to 2022 are shown in Figure 2, and basic information such as coastline length and type is shown in Figure 3.

Figure 3 shows that the total length of the coastline of Fujian Province generally tended to first decrease and then increase from 1992 to 2022. However, the length rebounded slightly in 2007. The largest change occurred between 1992 and 2012, with a decrease of 11.5%. The total length of the natural coastline decreased rapidly from 1992 to 2017, with a total decrease of 1196.0 km, but it rebounded slightly from 2017 to 2022. The total length of the artificial coastlines has continued to increase over the past three decades, with a total increase of 852.2 km. However, the growth rate slowed after 2017.

The length changes of various types of coastlines in Fujian Province show that the length of bedrock coastlines continues to decrease and that sandy coastlines, biological coastlines, and muddy coastlines all show changes that first decrease and then increase. Mariculture coastlines have generally shown wave-like growth characteristics in the past thirty years; artificial construction coastlines have continued to increase.

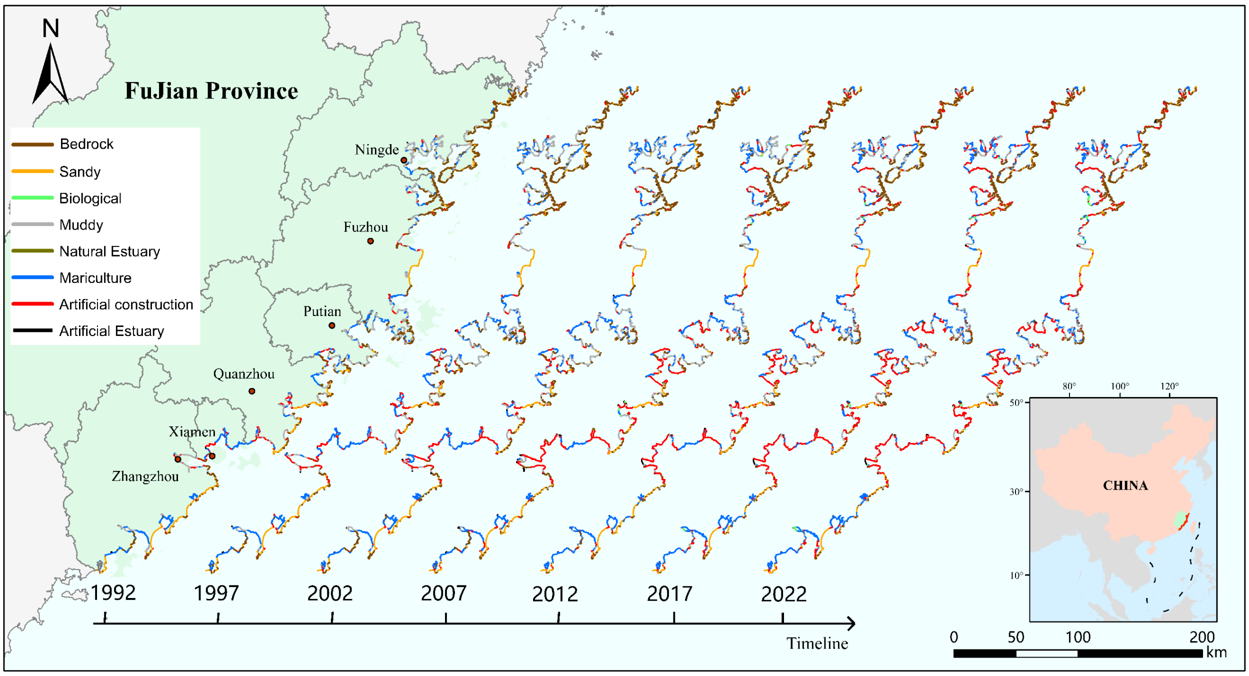


Figure 2. Evolution of coastline types in Fujian Province from 1992 to 2022.

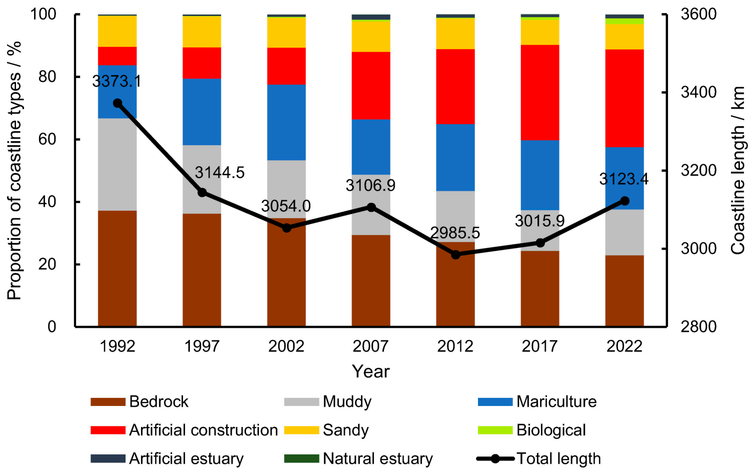


Figure 3. Changes in coastline length of Fujian Province from 1992 to 2022.

The spatial distributions of various types of shorelines also differ. Zhangzhou City in the south has a relatively developed mariculture industry due to its gentle terrain and many sandy beaches and tidal flats along the coast. There are many mariculture coastlines. The mainland coastline around Xiamen Island is economically developed, and most of the coastline has been transformed into artificial construction coastlines (seawalls, docks and other enclosures). Ningde City in northern Fujian is mountainous, and coastal development is much more difficult than in the southern region. Before the 21st century, most of its coastlines were undeveloped bedrock coastlines.

From 1992 to 2002, the total coastline length of Fujian Province decreased by 319.1 km, and the natural coastline length decreased by 659.2 km. The largest reduction was in the muddy coastline, most of which was converted to artificial construction coastline, followed by the conversion to mariculture coastline. The artificial coastline increased by 340 km, most of which developed from muddy coastline into artificial construction coastline, followed by reclamation into mariculture coastline. The reduction in coastline length during this period was related to the reclamation and mariculture of the muddy coastline at the mouth of the bay. The straightening of a large number of natural meandering coastlines led to a substantial reduction in the length of the coastline.

From 2002 to 2007, the total length of the coastline in Fujian Province increased by 52.9 km, and that of the natural coastline decreased by 93 km, mainly due to the loss of the bedrock coastline. The artificial coastline increased by 146 km, of which the artificial construction coastline increased by 311 km and the mariculture coastline decreased by 189.7 km. The development focus in the past five years has shifted to the in-depth development of developed areas, such as the reclamation of the sea on its original basis and the integration of small breeding ponds into large-scale breeding farms.

Between 2007 and 2012, the total length of the coastline in Fujian Province decreased by 121.4 km, the length of the natural coastline decreased by 238.8 km, and the lengths of both the bedrock coastlines and muddy coastlines decreased significantly. The length of the artificial coastline increased by 117.4 km, and the increase was concentrated in the mariculture coastline. Over the past five years, the expansion of artificial construction coastlines has slowed. The main change was the transformation of muddy coastlines into mariculture coastlines, which smoothed the coastlines and resulted in a reduction in the total length of the coastlines.

During 2012–2022, the total length of the coastline increased by 137.9 km, and the length of the natural coastline decreased by 110.8 km, mainly due to the decrease in the bedrock coastline. The sandy and muddy coastlines decreased slightly, but the biological coastlines increased significantly. The artificial coastline increased by 248.7 km, mainly due to the increase of 260.7 km in the artificial construction coastline, while the length of the mariculture coastline decreased by 17.8 km. Small-scale reclamation and breeding ponds are gradually being replaced by large-scale regulated seawater ponds. At the same time, reclamation and breeding behavior in some ecologically sensitive areas, such as bay estuaries, has been managed and regulated. As a result of these measures, the length of the mariculture coastline has been reduced in total by a small amount over the past ten years, but great progress has been made in standardization, as well as other areas.

From the above analysis, it is not difficult to see that from 1992 to 2022, the coastline of Fujian Province, China, experienced a large change. The coastline of Fujian Province, especially the coastline in the northern part of Fujian Province, has largely transformed from an original and natural coastline to an artificial and unnatural coastline. This reflects not only the development and destruction of coastline ecosystem services by local people but also the local people's pursuit of economic development and their yearning for a better life. Therefore, functional departments should develop reasonable planning and development layouts based on the current situation regarding Fujian Province's coastline and past coastline changes to simultaneously meet the needs of coastline ecological security and the development needs of the people of Fujian Province.

3.2. Coastline Ecological Index Dynamics

Table 6 shows the score results of the coastline ecological index subindicators. The scores range from 0 to 100. The higher the score is, the greater the degree of coastline ecology of the project during the study period.

Table 6. Coastline ecological index scores and rankings of Fujian Province.

Year	NSR	CVR	WQ	ICTD	SAI	DD	CEI	Ranking
1992	100.0	97.7	100.0	100.0	100.0	94.9	98.1	1
1997	72.3	100.0	68.4	57.9	77.3	93.6	80.5	2
2002	55.6	53.3	22.1	45.6	64.3	34.4	44.4	3
2007	42.3	46.2	3.5	0.0	38.0	0.0	16.6	7
2012	24.0	0.0	8.6	3.5	24.6	37.3	20.7	6
2017	0.0	8.3	10.7	26.3	0.0	75.8	31.8	5
2022	4.7	14.5	0.0	12.3	0.6	100.0	37.6	4

Figure 4 shows that the CEI first decreased and then increased from 1992 to 2022. In 1992, it ranked first with a total score of 98.1; in 1997, it ranked second with 80.5 points; and in 2007, it received the lowest score in the CEI, ranking seventh. Starting in 2007, the CEI score began to rebound, and the score increased annually, reaching 37.6 points in 2022, ranking fourth.

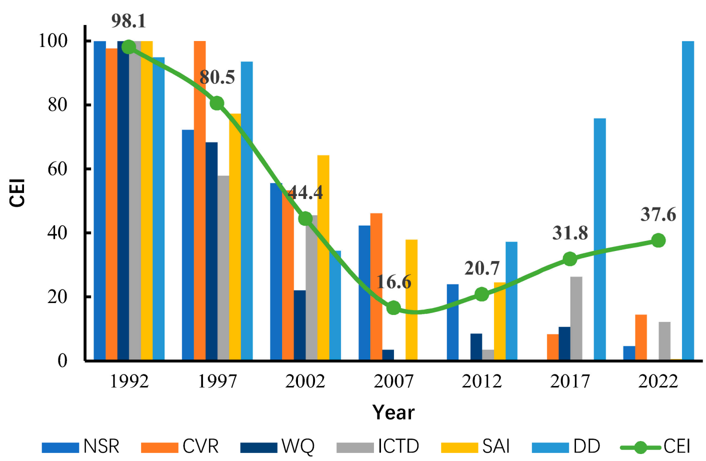


Figure 4. Coastline ecological index score of Fujian Province.

Between 1992 and 2007, the natural coastline retention rate continued to decrease, from 76.8% in 1992 to 59.2% in 2007, and a large number of natural coastlines were transformed into artificial coastlines. The vegetation coverage rate of the coastal zone decreased from 60.1% to 52.7%. The index of coastline type diversity continued to increase from 0.732 to 0.789, and the ecological level gradually decreased. The degree of artificial utilization of the coastline increased steadily over the past ten years, from 129.4 to 163.9, which represents the rapid expansion of the impact of human activities on the coastline. The dynamic degree of the coastline gradually increased over the past ten years and remained at a high level, which represents the increase in the expansion of the coastline by human activities. From 1992 to 2007, the CEI of Fujian Province decreased from 98.1 points to 16.6 points, and the score decreased to its lowest value in 30 years. During this period, the massive increase in reclamation projects and the disorderly development of reclamation and breeding greatly impacted the ecological environment of the coastline of Fujian Province, further affecting the score of the coastline ecological index.

From 2007 to 2022, the natural coastline retention rate in Fujian Province decreased from 59.2% to 46.3% and then rebounded to 47.7%, a decrease of 19.4%, and the natural coastline was further damaged. Coastal vegetation coverage continued to decline, from 52.7% in 2007 to 46.1% in 2012, and then rebounded to 48.1% in 2022. The index of coastline type diversity first decreased and then increased during the past fifteen years, and the results showed a slight decrease. The coastline artificial index first increased and then decreased slightly in these fifteen years, decreasing to 184.7 in 2022. The coastline dynamic degree decreased from 15.70 to 8.38. During this period, the change range of the coastline gradually decreased, and the coastline as a whole tended to stabilize. From 2007 to 2022, the CEI of Fujian Province increased from 16.6 points to 37.6 points. During this period, the development of the coastline in Fujian Province began to tighten compared with that before 2007, and the coastline gradually tended to experience planned and controlled development and utilization. The ecological conditions of the coastline greatly improved, and the CEI score steadily recovered. As a result, it can be considered that Fujian Province's coastline underwent an ecological recovery between 2007 and 2022, and that the score will continue to increase over time.

In summary, the coastline ecological index score continued to decline from 1992 to 2007, and gradually increased from 2007 to 2022.

4. Discussion

4.1. Coastline Change Analysis

From 1992 to 2022, Fujian's coastline length decreased by 249.7 km, including a reduction of 1196.0 km in natural coastline and an increase of 852.2 km in artificial coastline. Li, L. et al. [68] posited that the coastline length would decrease rapidly with increased human activity intensity before stabilizing, which aligns with this study's findings. Similarly, Wang, Y. X. [69] observed that from 2000 to 2020, the length of Fujian's coastline grew, with an increasing proportion of artificial coastline, consistent with this study's results from 2002 to 2022.

Human activities have influenced coastline length in two primary ways [68]. Firstly, land reclamation in areas with high fractal dimensions, such as bays, has smoothed natural coastline bends, thereby reducing coastline length. Secondly, the expansionary reclamation of flat coastlines and the filling of straits to convert islands into peninsulas have increased coastline length. Most changes in Fujian's coastline length from 1992 to 2022 can be attributed to these methods. For instance, Yang, C. et al. [70] found large-scale reclamation and expansion in Xinghua Bay, central Fujian, over the past 30 years, leading to increased coastline length. Lin, J. C. et al. [71] noted that China's rapid economic development post-2000 accelerated the expansion of artificial coastlines.

Analysis and verification with related studies confirm that the changes in Fujian's coastline length and type from 1992 to 2022 reflect the actual situation and are closely linked to sea use activities and economic development.

4.2. Coastline Ecological Index Consistency Analysis

The coastline ecological index score generally showed a trend of first declining and then increasing from 1992 to 2022. The increase and decrease in the score reflects the game process between the environment and development of the Fujian people over these thirty years.

At the end of the 20th century, people's awareness of environmental protection was not strong, and the environmental protection system was imperfect. In the process of economic development, it was inevitable to embark on the old path of "exchanging the environment for the economy". After Deng Xiaoping's "Southern Inspection" speech in 1992, the Fujian Provincial Government approved 237 key industrial satellite towns in coastal open zones to accelerate the development of coastal areas [72]. In 1996, Fujian Province issued the "Fujian Province Coastal Beach Reclamation Measures" to actively encourage the reclamation of tidal flats [73]; in 2002, the "Sea Area Use Management Law of the People's Republic of China" was promulgated to restrict and standardize the development and management of the ocean [74]. However, due to the introduction of relevant policies for the first time and the pressure of economic development, the new law did not put good restrictions on the disorderly development of the coastline.

Due to policies issued by the Chinese government and the Fujian Provincial Government encouraging the development and utilization of coastal and offshore areas, coupled with the relative weakness of environmental protection laws at the time, the proportion of primary, secondary, and tertiary industries in Fujian Province's marine economy shifted significantly. From 1995 to 2011, these proportions changed from 63:7:30 to 8:44:48 [75], reflecting rapid development in the marine industrial economy. It is important to note that, in absolute terms, every industry has been growing, albeit at different rates. According to the *China Marine Statistical Yearbook*, the proportion of Fujian Province's marine economy within the total provincial economy increased from 7% in 1995 to 25% in 2010 [76]. The total marine economic output reached CNY 424.752 billion in 2010. Whether through marine aquaculture or the development of the marine industry, this will destroy the original natural coastline.

Therefore, after fifteen years of rapid development, the ecological condition of Fujian Province's coastline has rapidly deteriorated, the retention rate of natural coastlines has dropped rapidly, and the water quality of offshore waters has deteriorated sharply. In contrast, the artificial utilization of coastlines has increased rapidly. The CEI of Fujian Province declined rapidly from 1992 to 2007.

With the introduction of the idea of ecological civilization in China, coupled with the enhancement of environmental awareness and the improvement of the environmental management system, Fujian Province has embarked on an ecological civilization path. Fujian Province has explored an ecological civilization social development model that combines protection with development and the harmonious coexistence of man and nature, responding to the Fujian people's yearning for a better life and a good environment. After 2007, the Chinese government and the Fujian Provincial Government successively issued many coastline protection measures and developed appropriate institutional measures for coastline ecological protection. During this period, in 2012, the State Council launched "The National Marine Functional Zoning (2011–2020)", proposing to carry out coastal zone remediation and restoration projects, and put forward strict restrictions on the use of coastal zones [50]. In 2015, the Central Committee of the Chinese Communist Party issued the "Overall Plan for the Reform of the Ecological Civilization System" to strictly control the use of natural coastlines [77]; after that, many regions began to expand the reclaimed areas that had already been put into use, resulting in an increase in the length of the coastline. In 2017, the Ministry of Natural Resources issued the "Coastline Protection and Utilization Management Measures", which became the first dedicated coastline protection law [78].

Based on the policies of the Chinese central government, the Fujian Provincial Government has also protected the province's coastline at the legislative level. It has issued policy documents such as the "Fujian Provincial Coastal Protection and Utilization Management

Regulations" and the "Fujian Provincial Plan for Strengthening Land and Sea Coordination to Promote Coastal Ecological Environmental Protection and Create a Beautiful Coastal Zone" to strengthen the protection and restoration of the coastline. Under the guidance of ecological civilization ideas and the above-mentioned laws and regulations, Fujian Province has completed a series of ecological protection and restoration projects, including the Minjiang River Estuary and Xiamen Bay. Fujian's marine economy reached CNY 1.2 trillion in 2019. While developing the economy with high efficacy, we also deliver a high-quality development answer sheet for natural resource management.

After the above policies and measures were promulgated, the development of the coastline became greatly restricted, and Fujian Province began to repair the damaged and ecologically poor coastline. The rate of decline in the natural coastline retention rate decreased rapidly until the natural coastline retention rate rebounded, the coastal vegetation coverage rate became stable, and the offshore water quality was restored. The CEI of Fujian Province gradually and steadily recovered after 2007.

In fact, China's past game between economic development and environmental protection, as well as the development of environmental protection and ecological civilization in recent years, prove that China has passed the turning point in the Environmental Kuznets Curve [79] and is moving in the direction of environmental health. This is also the reason why the CEI began to recover after the lowest value in 2007.

In addition to the impact of human activities, the coastline of Fujian Province is also affected by natural factors, including estuary siltation and erosion [70], but the affected areas are usually small and the change rate is extremely slow, so they are not discussed in this study.

After a comparison, it can be found that major events related to coastline development and protection in Fujian Province can be reflected in changes in CEI values to a considerable extent. That is to say, the coastline ecological index can reflect the changes in the degree of coastline ecology under the background of policy regulation and economic development well. The comprehensive evaluation index system of coastline ecology can be considered to have considerable universal applicability. However, we still need to pay attention to the rational and sustainable development of natural coastlines, address the relationship between nature and humans, and provide space for the sustainable development and utilization of coastline resources in the future. This will include protecting the original coastline landscape, conducting in-depth development of the reclaimed coastline, conserving biological resources such as coastal mangroves, and developing marine ecological fisheries. The rational development and utilization of coastline resources are conducive to comprehensively improving and ensuring coastline ecological security.

4.3. Limitations and Future Research Directions

Although this study proposed a new index method for coastline ecological assessment and successfully applied it to the evaluation of coastline ecology in Fujian Province, China, it is not without limitations. The number of selected sub-indicators is limited, and their mutual substitutability is insufficient. Future research should consider incorporating more sub-indicators to enhance the universality of the index. Additionally, the index has only been applied in Fujian Province, China, and requires further application in other regions to verify its universal applicability to coastlines elsewhere.

Future research could benefit from utilizing higher-resolution remote sensing image data sources to achieve greater accuracy in coastline extraction. Moreover, while the current study focuses on long-term changes in the coastline, future research should also calculate coastline ecological indexes for different seasons. This would allow for within-year comparisons of coastline ecology and provide valuable data support for related studies.

5. Conclusions

This study has developed a new and comprehensive evaluation index system for coastline ecology, named the Coastline Ecological Index (CEI). The effectiveness of this index was demonstrated through a case study assessing coastline ecology in Fujian Province, China, spanning from 1992 to 2022.

The analysis of coastline extraction revealed a fluctuation in Fujian Province's coastline length over the study period. Initially, from 1992 to 2012, there was a decrease from 3373.1 km to 2985.5 km, followed by an increase to 3123.4 km by 2022. This change was accompanied by a significant transformation of natural coastlines into artificial ones. The results of the case study indicated a corresponding variation in the CEI value for Fujian Province's coastline. It decreased from 98.1 points in 1992 to 16.6 points in 2007, and then gradually rose to 37.6 points by 2022.

An analysis of the factors driving these fluctuations in CEI values revealed a strong correlation with human activities influenced by economic development and policy regulations. Prior to 2007, Fujian Province prioritized economic growth over coastline ecology protection, resulting in the degradation of natural coastlines and a decline in CEI values. However, post-2012, a shift towards balanced economic development and environmental conservation led to the effective protection of coastline ecology, resulting in the recovery of CEI values.

This study's contribution lies in the construction of a universally applicable coastline ecological evaluation index system. This system accurately reflects the ecological impacts of coastline changes and offers simplicity, objectivity, and universality. With its straightforward index calculation and reasonable weight distribution, it holds potential for widespread adoption in coastline ecology evaluations across diverse regions worldwide.

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