remote sensing

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A Framework for Assessing the Dynamic Coastlines Induced by Urbanization Using Remote Sensing Data: A Case Study in Fujian, China

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Abstract: The coastline plays an important role in indicating the conditions of social-economic development in the coastal zone. In this study, an integrated assessment framework was proposed to address the provincial and county-level spatiotemporal dynamics of continental coastlines from the perspectives of length, position, composition, and anthropogenic utilization quantitatively, and to explore the exact impacts of urbanization on coastline changes in the Fujian Province over the period from 1985 to 2020. Results showed that the total length of coastlines decreased first and then increased due to the different patterns of economic development. The proportion of artificial coastlines and the index of coastal utilization degree increased rapidly during the same period. Moreover, the seaward movement of coastlines due to the coastal reclamation projects resulted in a considerable increment in land areas. The pressure brought by the continuous concentration of population, built-up areas, and industrial districts under the rapid urbanization was the primary factor that increased the degree of anthropogenic disturbances in the coastal zone. Furthermore, the policies issued by the local or central government can be critical tipping points for coastline changes in different periods.

Keywords: dynamics of coastlines; assessment framework; urbanization; human activities; policies

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1. Introduction

The coastal zone is of great value to coastal communities but faces great threats worldwide [1]. It is important to track the changes in coastal zones by a simple but representative indicator from a large spatiotemporal scale. The dynamic coastlines are the result of the integrated impacts of human activities and climate changes in coastal zones. It can not only reflect comprehensive interactions between land and sea but also indicate the development and degradation of coastal lands [2]. Therefore, tracking the changes in coastlines is an effective way to monitor the condition and access ecosystem health of coastal zones.

In many developing coastal countries, e.g., China, the coastline has witnessed unprecedented changes due to rapid urbanization over the past decades such as the coastlines of China's mainland changed in spatial location, length, composition, and geometric structure. Coastal reclamation projects have led to the continuous movement of coastlines to the ocean with rapid urbanization in coastal zones. The length of the continental coastline changed sharply, increasing from 18.1 × 10^3 km to 19.7 × 10^3 km, and the proportion of artificial coastline increased from 18.30% to 64.08%, from 1940 to 2014 [3]. Moreover, most coastal wetlands are degraded, even lost due to human activities [4]. More than 12,000 km^2 of coastal wetlands along China's coastline were reclaimed for economic purposes [5].

Therefore, it is of great emergency to understand the spatiotemporal dynamics of coastlines under the impacts of rapid urbanization and the relevant geopolitical influences.

Since the first launch of the earth observation satellite in the 1970s, many studies have made great efforts in the quantitative analysis of spatiotemporal changes in coastlines using remote sensing images. Boak and Turner made a detailed description of coastline types from the perspective of RS, which provided a scientific standard for coastline research [6]. Based on the high-frequent revisiting period and nearly half-century historical records, remote sensing images are able to delineate the spatiotemporal changes of coastlines in detail. Li et al. used the images obtained by different RS satellite sensors to track the changes in the coastline of the Pearl River Estuary from 1980 to 2003 [7]. Gao et al. conducted a long-term temporal and spatial change analysis of the continental coastlines of the Chinese mainland in combination with time series Landsat images and the digital shoreline analysis system (DSAS) [8]. Due to more and more effects of human activities in different forms, many studies began to explore the influences of the anthropogenic stressors on coastline changes. On one hand, the dynamics of coastlines can be used as a direct indicator to show the seaward movement of human activities in coastal zones, such as land reclamation for ports, aquaculture, and industry [9,10]. On the other hand, many works were conducted to assess the impacts of human activities on coastline changes quantitatively. Zhang et al. used the ratio of area change caused by coastline utilization to quantify the intensity of coastline development [11]. In addition, the index of coastal utilization degree (*ICUD*) was used to quantify the contributions of land uses to coastline changes by human activities [3]. However, previous studies paid less attention to how the coastline changed with local economic development and issued policies. With the increasing complexity of human activities in coastal zones, therefore, an assessment framework is required to evaluate the dynamics of coastlines and to reflect the conditions of coastal zones in space and time.

In this study, we proposed an integrated assessment framework to explore the spatiotemporal dynamics of continental coastlines under the impacts of rapid urbanization and economic growth in developing coastal zones. The Fujian Province was taken as a case area and the analysis of provincial and county-level dynamics of coastlines was conducted to evaluate the effects of urbanization on changes in coastlines over the period from 1985 to 2020. Based on the results, we can reveal: (1) the spatiotemporal changes of the continental coastline in Fujian Province, and (2) uncover the relationship between coastline dynamics and anthropogenic stressors, such as local economic development and issued policies in the Fujian Province under rapid urbanization.

2. Study Area

The Fujian Province is located in the southeast of China (23°33′–28°20′N and 115°50′–120°40′E), dominated by the subtropical monsoon climate. The continental coastline of the Fujian Province is very tortuous with 125 bays developed. The total land area of the Fujian province is 121,400 km^2. The overall terrain is high in the northwest and low in the southeast, dominated by mountains and hills with a coverage of about 90% of the total area, leading to a dense population in the coastal area. There are six prefecture-level cities with a total of 29 counties in the coastal zone of the Fujian province (Figure 1). The coastal areas support nearly 80% of the population and produce 82.85% of the economy of the Fujian province. Fujian not only has a vast offshore fishing ground but also has plenty of tidal flats for breeding a variety of seafood, with a fishery output value of CNY 136.17 billion in 2021 [12]. Since the reform and opening up, the population in coastal areas of Fujian Province has increased, the economy has developed rapidly, and the rate of urbanization in Fujian's coastal zone accelerated. A total of 29 counties along with Fujian's coastline were selected as the scope of this study to quantify the impacts of urbanization on the changes in coastline (Figure 1).

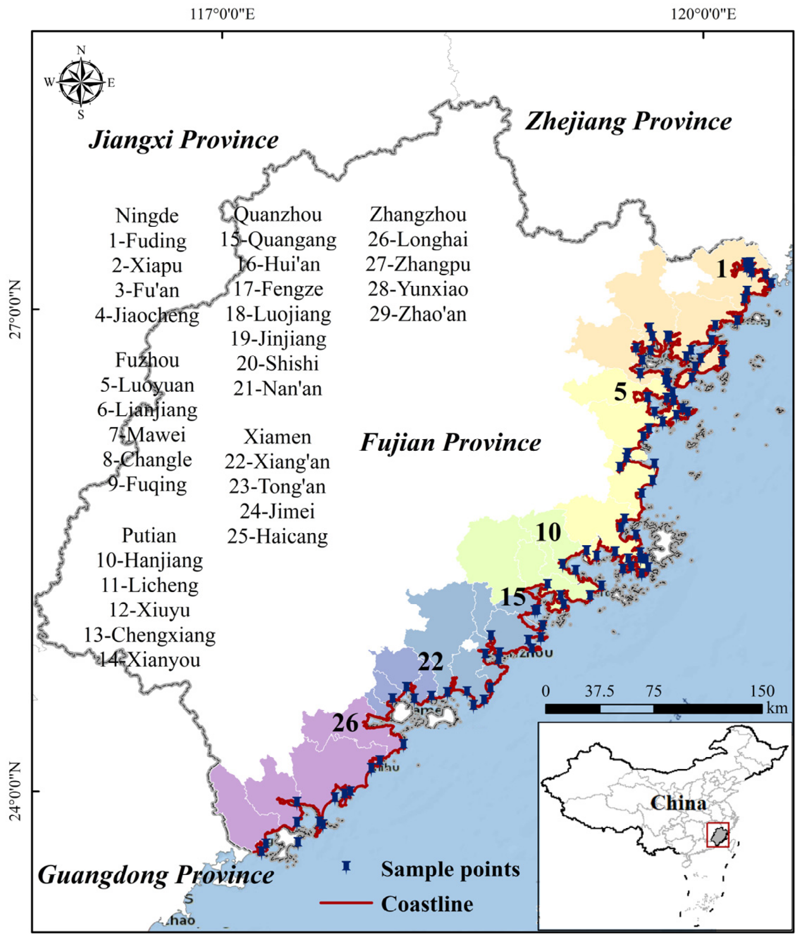


Figure 1. Geographical settings of Fujian Province.

3. Data and Method

3.1. Data and Pre-Processing

In this study, 91 scenes of Landsat series satellite images, including Landsat-5 TM, Landsat-7 ETM+, and Landsat-8 OLI, provided by the United States Geological Survey (https://earthexplorer.usgs.gov/ (accessed on 6 September 2020)), were used to track the spatiotemporal changes of coastline in Fujian province with a spatial resolution of 30 m from 1985 to 2020. Most of the images were acquired from October to December with good quality to ensure temporal consistency. All images were projected to the WGS-1984 coordinate system.

To quantify the impacts of human activities on the coastline, we also collected socio-economic data, including resident population and GDP from China Statistical Yearbook. Moreover, an NPP-VIIRS-like nighttime light data, which is highly relative to human activities, was employed as an auxiliary indicator of human activities in the coastal zone. The descriptions of all data used in the study are shown in Table 1.

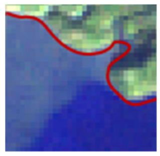
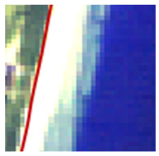
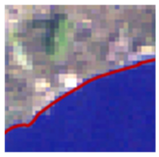
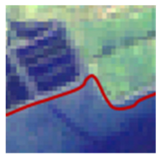
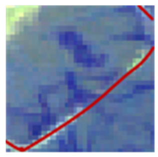
Table 1. Employed datasets in this study.

Data	Sources	Timespan
Landsat Images	https://earthengine.google.com/ (accessed on 6 September 2020)	1985–2020
Nighttime light data	DOI:10.5194/essd-2020-201 [13]	2000–2018
Population and GDP	http://www.stats.gov.cn/ (accessed on 10 July 2021)	1985–2020
GF-2 Images	Geomatic Center of Fujian Province	2020
Significant wave height dataset	http://doi.org/10.11922/sciencedb.j00001.00038 (accessed on 10 July 2021)	2018

3.2. Detection of the Continental Coastlines

The coastlines of Fujian Province were classified into 7 categories [14]. The natural coastlines were classified into rocky coastlines, sandy coastlines, and muddy coastlines, and the artificial coastlines include urban coastlines, port coastlines, commodity coastlines, and unused coastlines (Table 2) [15,16].

Table 2. Categories of continental coastline in Fujian Province.

Categories		Features	Sample Images
Natural coastlines	Rocky coastlines	The boundary between a cape or vertical cliff and the ocean with a clear edge.	
	Muddy coastlines	The boundary of muddy flats with natural vegetation grows on.	
	Sandy coastlines	The boundary of the ridge-like sandy sedimentary belt on the beach.	
Artificial coastlines	Urban coastlines	The boundary between human settlements and the sea with regular and clear edges.	
	Port coastlines	The boundary of ports with regular geometric structure.	
	Commodity coastlines	The boundary of reclamation projects for aquaculture and agriculture.	
	Unused coastlines	The boundary of reclaimed areas but not been used yet.	

This mapping of coastlines was conducted based on pre-processed Landsat images acquired during relative high tide with visual interpretation [17]. Because there are a large number of rocky coasts with high stability, the dynamic updating of the coastline year by year is adopted to improve the accuracy and ensure the consistency of the unchanged part of the coastline in the previous periods. The latest coastline in 2020 was used as the baseline to extract the previous coastline by updating the changed segment of coastline period by period. Finally, the coastlines of 13 periods from 1985 to 2020 were portrayed.

The accuracy of coastline mapping was verified by the control points that were selected on the GF-2 high-resolution image in 2020. Standard deviation (*SD*), which is generally used to detect the deviation between the predicted value and the real value, was used to evaluate the accuracy of the coastline [18]. The expressions are as follows:

$$SD = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(y_i - \hat{y}_i)^2} \quad (1)$$

where m is the total number of test samples, y_i is the predicted value, and $\hat{y}_i$ is the mean of all samples. The total number of ground control points (GCPs) was 100. The accuracy of extracted coastlines was evaluated by the mean distance and SD between the GCPs and results from images. In the relationship between uncertainty P and resolution A [19], it is found that there is a certain mathematical relationship between them with the following equation:

$$P = \frac{2\sqrt{2}}{3} \times A \quad (2)$$

Therefore, the maximum allowable error of line feature information extraction from a 30 m resolution remote sensing image is 28.28 m [20].

3.3. Framework for Assessing the Dynamics of Coastlines

In this study, a comprehensive evaluation framework was proposed to assess the dynamics of coastlines in time and space (Figure 2). Firstly, the historical change of coastline was delineated in perspectives of length and composition, as well as the intensity of human activities. Then, the movement of coastlines was analyzed quantitatively in space. Thirdly, integrating with the social-economic data and nighttime light data, the main driving forces of coastline change were explored.

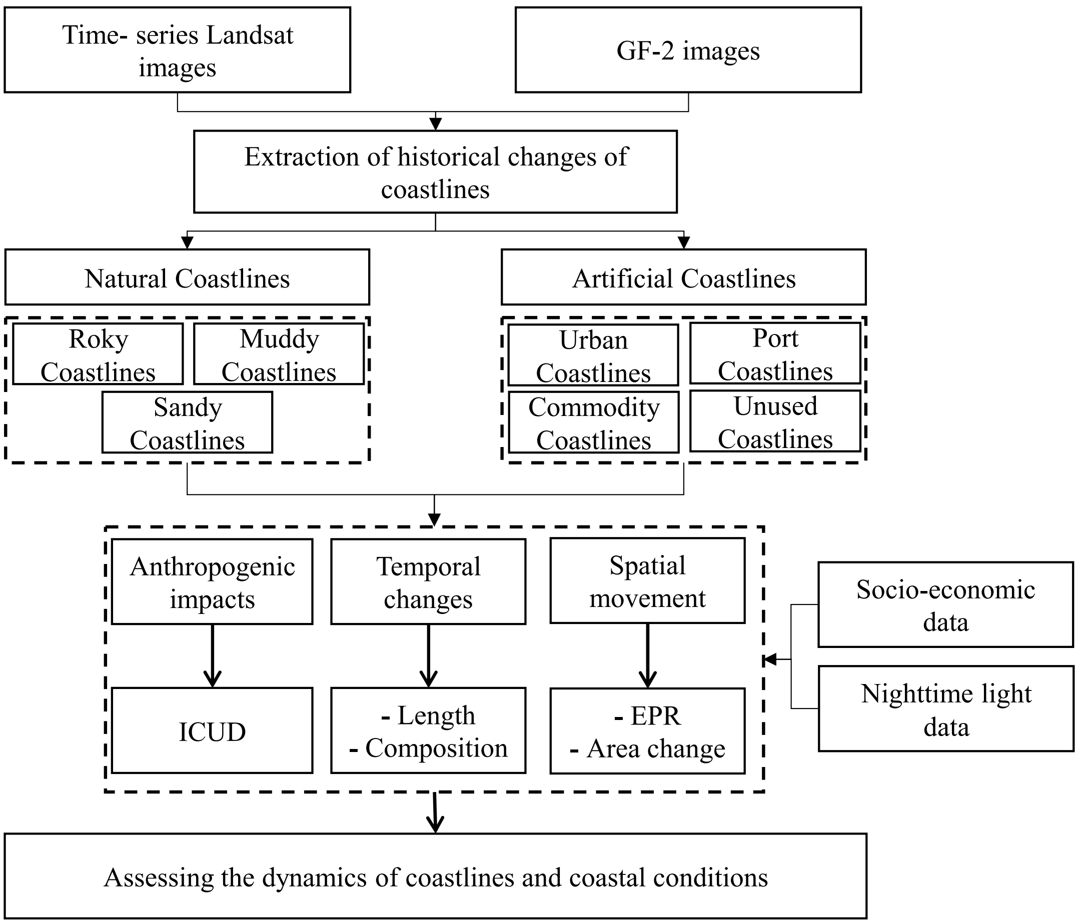


Figure 2. The framework to assess the dynamics of coastlines.

3.3.1. Assessing Temporal Changes in Coastline

The length change intensity (*LCI*) of the coastlines was used to evaluate the length change rate of the coastline [18]. The *LCI* represented the average annual change of the length of the coastline type in a certain period. It was calculated by the following equation:

$$LCI_{ij} = \frac{L_J - L_i}{L_i} \times \frac{1}{j-i} \tag{3}$$

where LCI_{ij} is the *LCI* of a certain type of coastline from the i_{th} year to the j_{th} year; L_i is the length of a certain coastline in the i_{th} year; L_j is the length of a certain coastline in the j_{th} year.

The proportion of a certain type of coastline length in the total length (P_h) was used to represent the composition or proportion relationship between different types of coastline at a certain time. It was calculated by the following equation:

$$P_h = \frac{L_h}{\sum_{h=1}^{n} L_h} \times 100\% \tag{4}$$

where L_h is the percentage of the structure of the type, h is a certain type of coastline in the total coastline length in a certain year; $\sum_{h=1}^{n} L_h$ is the total length of all types of coastlines in the same year.

3.3.2. Mapping the Spatial Dynamics of Coastlines

The ending point rate (*EPR*) was used to assess the spatial dynamics of the coastline in Fujian province owing to erosion, deposition, and reclamation quantitatively. The *EPR* was calculated based on the distance of coastline movement between the oldest and the youngest coastline [21]. The positive value represents a sea-ward movement of the coastline. The calculation formula is as follows:

$$NSM = D_{latest-oldest} \tag{5}$$

$$EPR = \frac{NSM}{T_{latest} - T_{oldest}} \tag{6}$$

where NSM is net coastline movement, the distance (m) between the oldest and the latest coastlines along the transect that is perpendicular to the coastline; T_{latest} is the year of the latest coastline and T_{oldest} is the year of the oldest coastline. A total number of 55,988 transects that are perpendicular to the coastline were generated with an interval of 50 m along with Fujian's coastline. Then, the distance between the coastline between 1985 and 2020 was measured and the *EPR* of the coastline was calculated at every transect. Finally, the area change of the land, including the area erosion and accretion was calculated at the county level.

Moreover, the geometric shape obtained by calculating the movement of coastline in different periods was intended to represent the spatial change degree of coastlines [22], reflect the spatial distribution difference of coastline change, and more intuitively show the spatial expansion or erosion degree of coastline. Meanwhile, the percentage change of movement was employed to show the relative change of coastlines in every county with the following equation,

$$Percentage = \frac{M_i}{S_i} \times 100\% \tag{7}$$

where M_i is the accretion or erosion area of the i_{th} district; M_i is the total area of the i_{th} county.

3.3.3. Quantifying the Anthropogenic Impacts on Coastlines

The index of coastline utilization degree (*ICUD*) was employed to assess the impacts of human activities quantitatively on the coastline of Fujian province, which is based on the concept and model of the comprehensive index of land use degree [19] and can characterize the intensity of the impacts of human activities on different types of the coastline. The equation of *ICUD* was calculated as follows:

$$ICUD = \sum_{i=1}^{n} (A_i \times C_i) \times 100\% \quad (8)$$

where A_i is the length proportion of i_{th} type coastline of total length in the year; n is the number of coastline types, and C_i is the human action intensity index determined by the type of coastline. In general, though human activities have fewer impacts on the natural coastlines they can still be affected by the surrounding human-related environments. Therefore, the C_i of natural coastlines were set as 0.1. For the artificial coastline, the urban coastlines are affected by human activities most, followed by ports, commodities, and unused coastlines. The C_i of them were set as 1, 0.8, 0.6, and 0.2, respectively. According to the experience of field investigation and an improvement model [23], the C_i was set with the value of 0–1 (Table 3). The greater *ICUD* value represents the higher impacts of human activities on the coastline and the higher degree of economic development of the coastal zone. The correlation analysis of *ICUD* was conducted with population, GDP, and nighttime light data, to verify the capacity of *ICUD* in representing the degree of coastal social-economic development. The natural breakpoint method was used to classify the results into four levels: very low (0–0.25), low (0.25–0.5), medium (0.5–0.75), and high (0.75–1).

Table 3. The intensity of human activities on different coastlines.

Coastline Type	Urban	Ports	Commodities	Unused	Rocky Coastline	Muddy Coastline	Sandy Coastline
C_i	1	0.8	0.6	0.2	0.1	0.1	0.1

4. Results

The validation results showed that the mean distance between the GCPs and coastline extraction results in 2020 is 18.21 m and the *SD* is 14.39 m, which is lower than the maximum allowable error. The corresponding coastline type of each control point is consistent with the extracted coastline type. Based on the results, we found that the coastlines in Fujian showed a great change in length, composition, location, and *ICUD* over the period from 1985 to 2020.

4.1. Changes in Length and Composition of Coastlines

The historical changes in length and composition of coastlines in the Fujian province showed significant variation in space and time over the past 35 years (Figure 3). The total length of continental coastlines increased from 2969.17 km to 3137.40 km from 1985 to 2020. A turning point occurred in 2000 when the total length of coastlines decreased from 1985 to 2000 but increased from 2000 to 2020 (Figure 3a). Most reduction of coastline occurred in the northern Fujian Province, such as Fuding (No.1), Xiapu (No.2), Fu'an (No.3), Luoyuan (No.5), Lianjiang (No.6), and Fuqing (No.9) from 1985 to 2000, and the length of coastlines increased from 2000 to 2020 with a relatively higher rate in almost all counties (Figure 3b).

The proportion of natural coastlines of the Fujian Province was more than 66% in 1985, which reduced to 33.46% at the end of 2020. Especially, the muddy coastlines decreased significantly with a rate of 19.83 km/yr over the past 35 years. The artificial coastline is increasing from 990.05 km to 2087.75 km. For example, the Urban and Ports increased rapidly with a rate of 13.05 km/yr and 13.04 km/yr, respectively. The composition of artificial coastlines increased from 33.34% to 47.43% over the period from 1985 to 2020. In terms of the composition of artificial coastlines (Figure 3a), the primary type of artificial coastline was the commercial coastline before 2000 with a maximum proportion of 73.69%. The proportion of port coastlines increased the fastest after 2000, especially in Quanzhou

City and Xiamen City. The proportion of port coastlines has increased by nearly 14% and the proportion of urban has increased from 14.51% from 2000 to 2020, respectively.

The historical changes in *LCI* of coastlines showed that artificial coastlines were more dynamic than natural coastlines (Figure 4a). The *LCI* of s artificial coastlines increased slowly before 2000. The ports, urban, and commodities coastlines changed significantly with *LCI* values of 31.38%, 13.69%, and 2.39% from 1994 to 1997, respectively. All kinds of artificial coastlines maintained high intensity, among which the Unused changed most significantly from 2003 to 2006, with an intensity of 39.17% from 2000 to 2012. *LCI* decreased gradually after 2012. In terms of space, Figure 4b illustrates the *LCI* of coastlines at the county level during 35 years, of which the ports changed the most. The fastest change intensity appeared in Fuqing (No.9), Hui'an (No.16), Shishi (No.20), Longhai (No.26), and Zhangpu (No.27) from north to south. Only Longhai (No.26) happened to be the highest *LCI* of reclamation, and other areas are mainly ports.

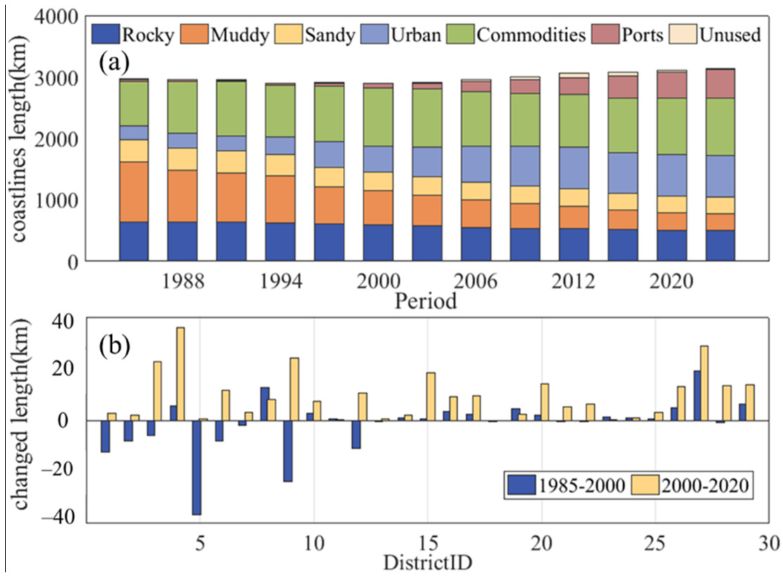


Figure 3. (**a**) Historical changes of length and composition of coastline in Fujian province; (**b**) Changes in length of coastline in 29 counties during two periods.

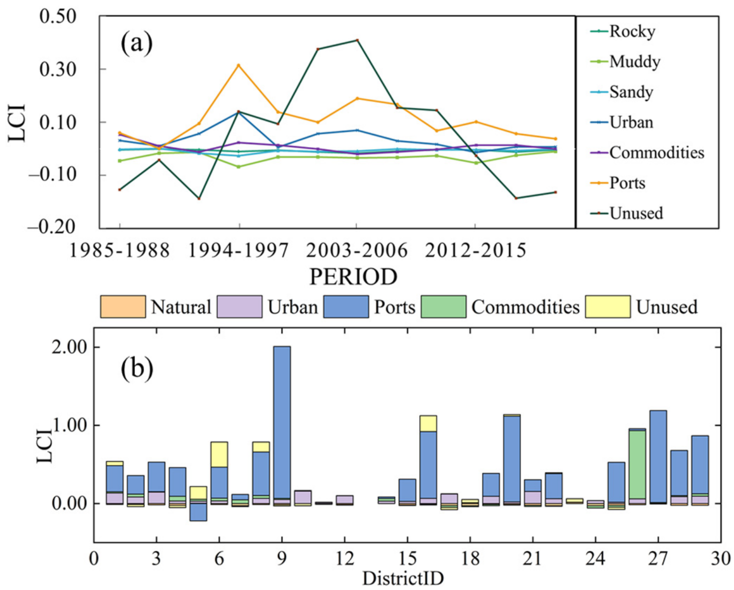


Figure 4. (**a**) *LCI* of all types of coastlines every three years from 1985 to 2020; (**b**) *LCI* of different coastlines in each district from 1985 to 2020.

4.2. Spatial Dynamics of Coastlines

The overall *EPR* showed a seaward movement of coastlines with a rate of 9.49 m/yr in the Fujian Province from 1985 to 2020. The maximum rate appeared in Fuqing (No.9), and the minimum rate appeared in Fuding (No.1) with the rate of 227.89 m/yr and −90.19 m/yr, respectively (Figure 5c). Totally, 90.93% of coastlines in the Fujian Province moved to the sea over the past decades. The average accretion and erosion of land area in coastal counties by the movement of coastlines were 18.25 km^2 and 0.10 km^2 (Figure 5b).

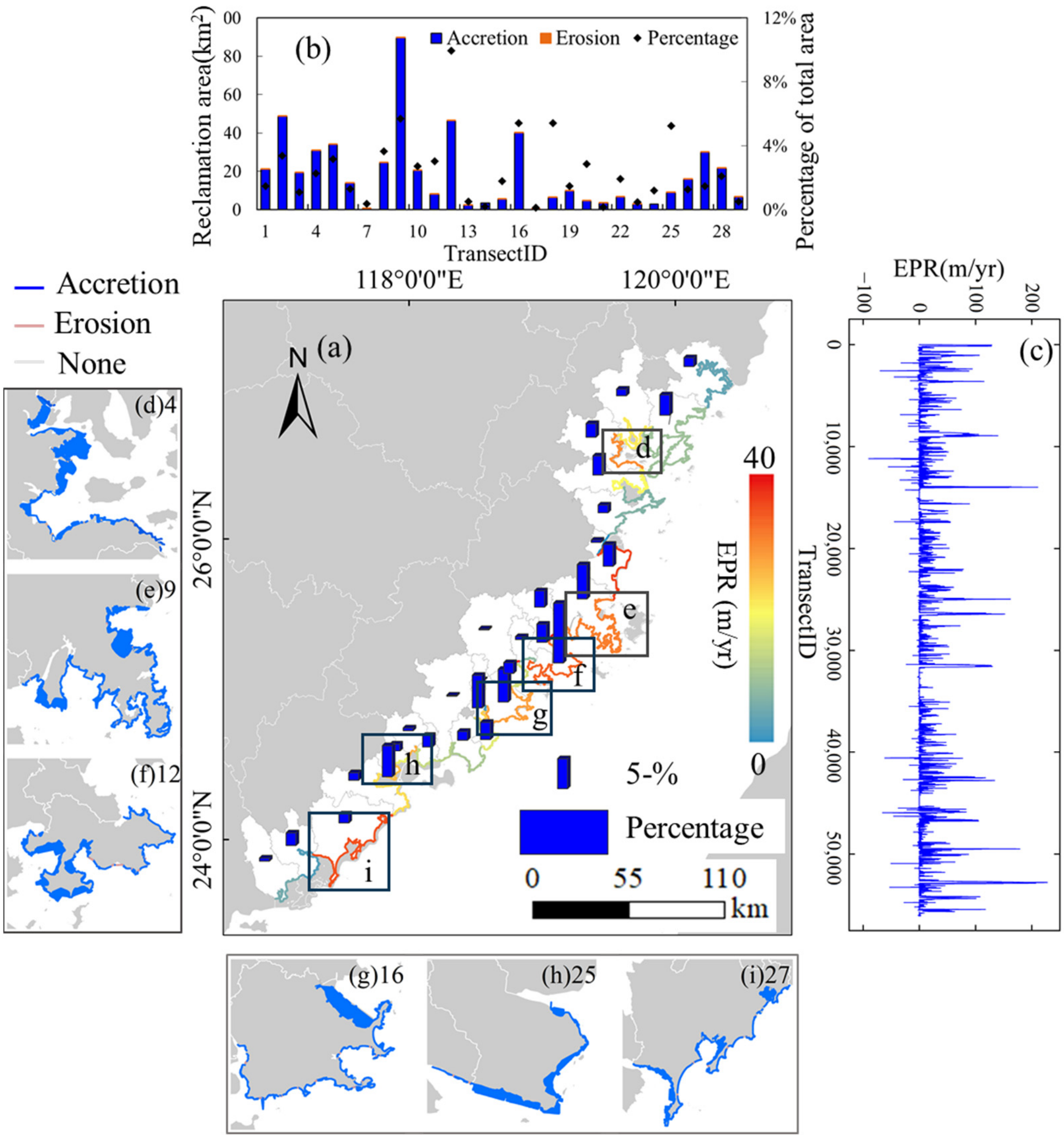


Figure 5. (**a**) *EPR* and the proportion of reclamation area in different districts; (**b**) reclamation area including accretion and erosion of each district; (**c**) *EPR* of the continental coastline of every transect; (**d**–**i**) Jiaocheng, Fuqing, Xiuyu, Hui'an, Haicang, Zhangpu Districts with huge dynamic change of *EPR* and reclamation area in different cities.

The mean *EPR* of coastlines in most cities was within 10 m/yr, meanwhile, we calculated the percentage of reclamation area in different districts to measure reclamation intensity (Figure 5b). Typical districts with high *EPR* included Jiaocheng (No.4), Changle to Xiuyu (No.8 to No.12), Xianyou to Haicang (No.24 and No.25), and Zhangpu (No.27). The highest rate occurred in Hanjiang (No.10) with an *EPR* of 38.34 m/yr, the second is Xianyou (No.24). The increments of reclamation in most counties were less than 30 km^2.

The most accretion of the land area occurred in Fuqing (No.9) with an area of 89.52 km^2. However, the highest percentage of accretion is in Xiuyu (No.12) (Figure 5b).

4.3. Changes in Coastline Utilization Degree

Historical changes in *ICUD* along coastlines of the Fujian Province increased continuously with an average value from 0.30 to 0.55 over the past 35 years. The *ICUD* of most districts was in the range of 0.3 to 0.6 before 2000 (Figure 6b). Then, *ICUD* in all districts increased in the 21st century with an average value from 0.40 to 0.70. The *ICUD* of Xiamen City was the highest with an average *ICUD* of more than 0.60 over the past decades. The *ICUD* of Mawei (No.7), Fengze (No.17), Luojiang (No.18), Tong'an (No.23), Jimei (No.24) were at Medium and High before 2000 (Figure 6a). By the end of 2020, Nan'an (No.21) and Haicang (No.25) also became districts that possessed high *ICUD* values, and their *ICUD* value of them, respectively, are 0.81 and 0.80. It can be found from Figure 6 that the maximum, minimum, and medium of *ICUD* changed greatly. It was found that there was an important turning point for *ICUD* in 1994 (Figure 6b). The *ICUD* of the coastline was at a low in all districts with a range from 0.36 to 0.40 before 1994, then increased quickly from 1994 to 2012. The other turning point was in 2012, after that, the *ICUD* of the whole coastline and different districts became stable. The *ICUD* of Quanzhou and Zhangzhou City increased greatly in the past 35 years. The highest annual change rate of *ICUD* is Fengze (No.17) with a mean rate of 1.27% from 1985 to 2020. The *ICUD* of Ningde City and Fuzhou City is relatively low, but in some areas, such as Jiaocheng (No.4) and Mawei (No.7), the *ICUD* values of these areas were higher with values of more than 0.67.

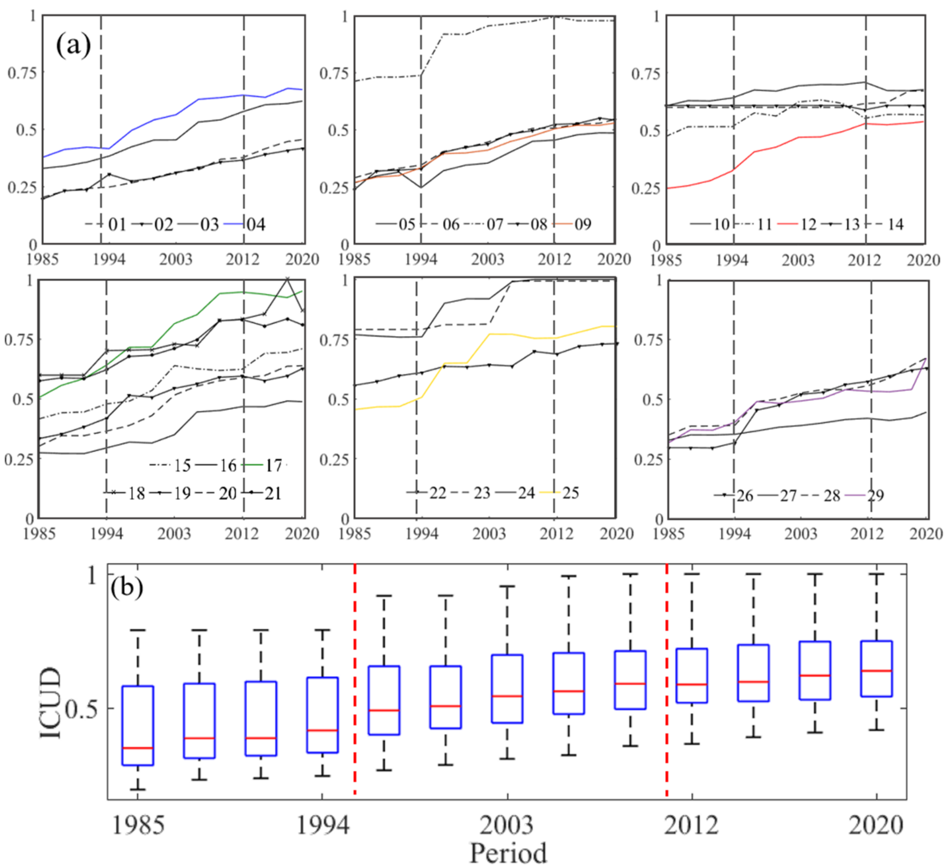


Figure 6. (**a**) The changing trend of *ICUD* in 29 counties; (**b**) Some basic statistical indicators of all *ICUD* in 13 different periods.

5. Discussion

Changes in coastlines show good capacities in assessing human activities in coastal zones separately in time and space. There is a strong linear relationship between coastline changes and some indicators for human activities, such as night light data, population, and GDP (Figures 7 and 8). The result shows that *ICUD* has a significant linear relationship with the three socio-economic data (Figure 7a–c). Moreover, the correlations between night light data, reclamation area, *EPR* and *ICUD* of coastline in every county were illustrated with all values less than 0.05 (Figure 8). In conclusion, based on the strong correlation between coastline changes and socio-economic data, it explains that the evaluation framework adopted in this paper has certain reliability to be applied in other coastal developing countries with rapid economic development and urbanization.

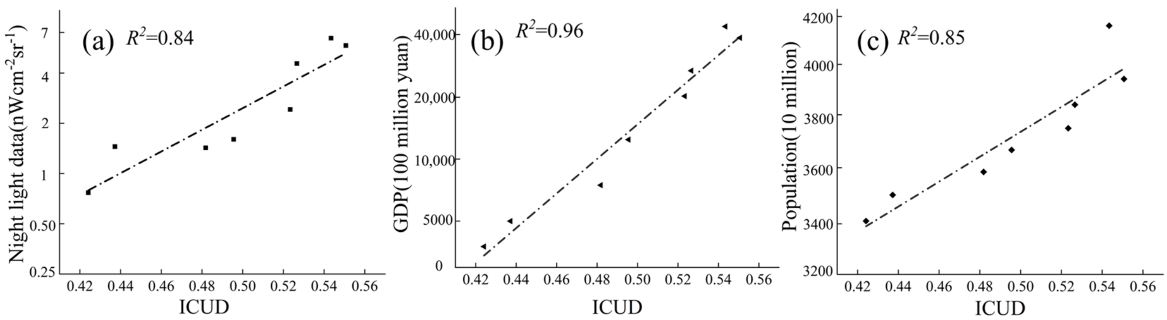


Figure 7. The relationship between *ICUD* and (**a**) night light data; (**b**) GDP; (**c**) population at the provincial level.

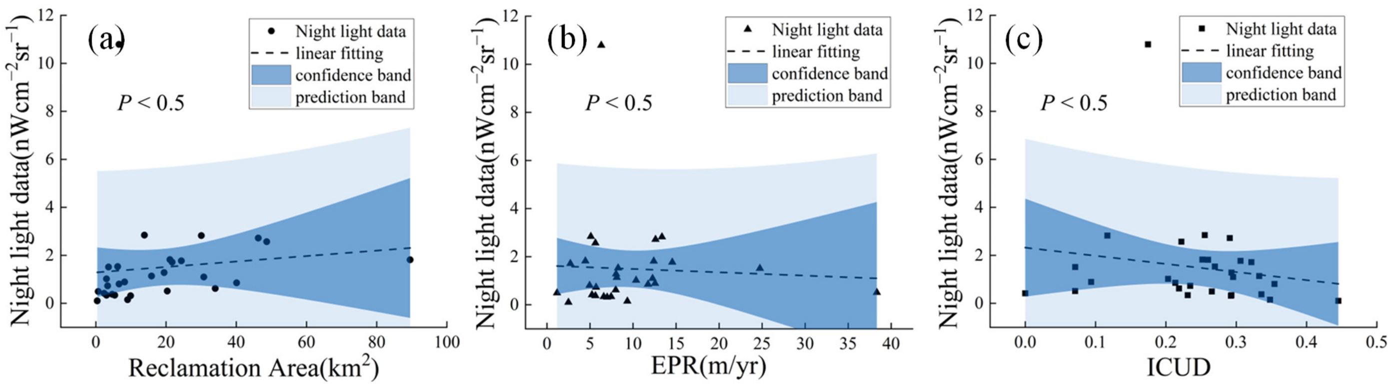


Figure 8. The relationship between night light data and (**a**) reclamation area, (**b**) *EPR*, (**c**) *ICUD* at the county level.

The continental coastlines of the Fujian Province changed significantly from 1985 to 2020 as a result of the impacts of human activities, such as social-economic pressure and policies. Due to the continuous urbanization and rapid economic development in coastal zones, human activity was the primary driver leading to the development and degradation of the coastlines [24]. The growth of population and the rapid development of the economy are the main driving forces for the rapid movement of coastal urbanization. With the continuous advancement of reform and opening up, the population and industrial districts in the coastal zone are continuously concentrated, and the level of urbanization continuously increased in the Fujian Province. The proportion of GDP and population in the coastal areas are significantly higher than that of inland areas. According to statistics, by the end of 2019, the population of coastal cities accounted for more than 80% of the total population of the Fujian Province, and the total GDP accounted for 82.85% of the province [25]. Due to the rapid urbanization caused by human activities, "to the sea" has become the main way to alleviate the pressure on coastal land and extend development space. The resident population and GDP are highly correlated with the *ICUD* values of the

Fujian Province (Figure 7a–c). It was also indicated by the relationship between changes in nightlight data and other social-economic indicators (Figure 8a–c).

The promulgation of policies is the guideline for local economic development from the central government in the coastal zone of China. The issuing time of policies often becomes a critical tipping point for the pattern of economic development in a specified period. Over the past period from 1985 to 2020, many policies from central or local governments were implemented in Fujian's coastal zone (Figure 9), leading to various development patterns of coastal zones indicated by changes in coastlines. In general, the total length of coastlines decreased from 1985 to 2000 and then increased from 2000 to 2020 since the different patterns of economic development (Figure 3b). From the late 1980s to the early 1990s, China set off the third reclamation upsurge focusing on aquaculture reclamation [26], and the commodities coastline continually increased (Figure 3). However, the total length of the continental coastlines was reduced due to the simple geometric structure of commodity coastlines from 1985 to 1997 (Figure 3a). With the implementation of the Regulations of Fujian Province on Agricultural Investment in 1997 [27], the local government paid more attention to industrial investment than agriculture since Fujian has finished the initial development in agriculture and aquaculture. Therefore, the length of the continental coastline of the Fujian Province continuously increased with the rapid development of artificial coastlines (Figure 3a) and *ICUD* also increased significantly, reaching the highest change intensity over the past 35 years (Figure 6b). The issue of the "Mini Three Links" policy in 2000 [28] has witnessed the Fujian Province gradually becoming an important trade port along the southeast coast of China with the increasing proportion of port coastlines, which led to the increment of the total length of coastlines indicated the complicated geometry of the port coastlines (Figure 4a). "The outline of putting forward the National Marine Economy Development Plan" [29] was issued in 2003, with a strategic goal of gradually building China into a marine power for the first time with the fourth upsurge of industrial reclamation. The development of artificial coastlines (i.e., port coastlines and urban coastlines) resulted in a significant increment in the continental coastlines (Figure 4b). With the ecological civilization construction adopted as a national strategy in 2014 and the Fujian Province was selected as a pilot demonstration of ecological civilization [30], the pattern of coastal development changed, which was indicated by the *LCI* and *ICUD* of coastlines (Figures 4 and 6a). In 2016, the Fujian Provincial Department of Oceans and Fisheries issued the Coastal Zone Protection and Utilization Plan of Fujian Province [31], aiming to further optimize land space and strengthen coastal ecosystem protection, Figure 4a shows that the *LCI* of each type of coastline has decreased to less than 10%. The State of Council issued "the circular on strengthening the protection of coastal wetlands and strictly controlling reclamation" in 2018 [32]. All reclamation projects are strictly prohibited, and most natural coastlines are protected, leading to nearly no changes in coastlines from 2018 to 2020 (Figure 3).

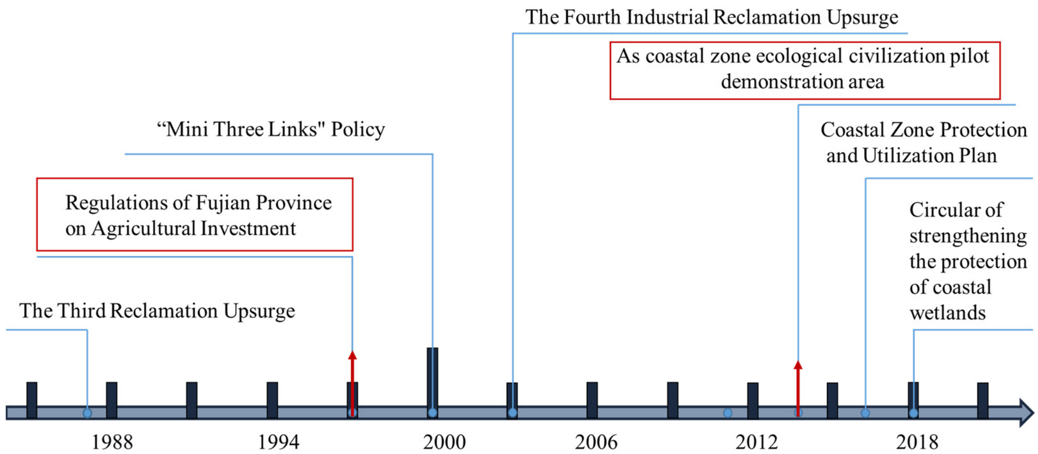


Figure 9. The relative policies issued by governments over the past decades.

Though most coastal areas gained accretion over the past decades, 9.07% of coastlines were still experiencing land loss or erosion due to human activities (Figure 10). Some reclaimed area, e.g., illegal coastal aquaculture ponds, was removed by the local government (Figure 10a). Moreover, part of the natural coastline was experiencing slight erosion, such as Xiapu (No.2), Fuqing (No.10), Xiuyu (No.12), and Hui'an (No.16). The potential causes of the erosion could be strong local hydrodynamics, and the significant wave height shows a correlation with erosion areas (Figure 10c). Furthermore, the impacts of other coastal hydrodynamics, such as coastal current, and sediment transportation, should be explored in future research.

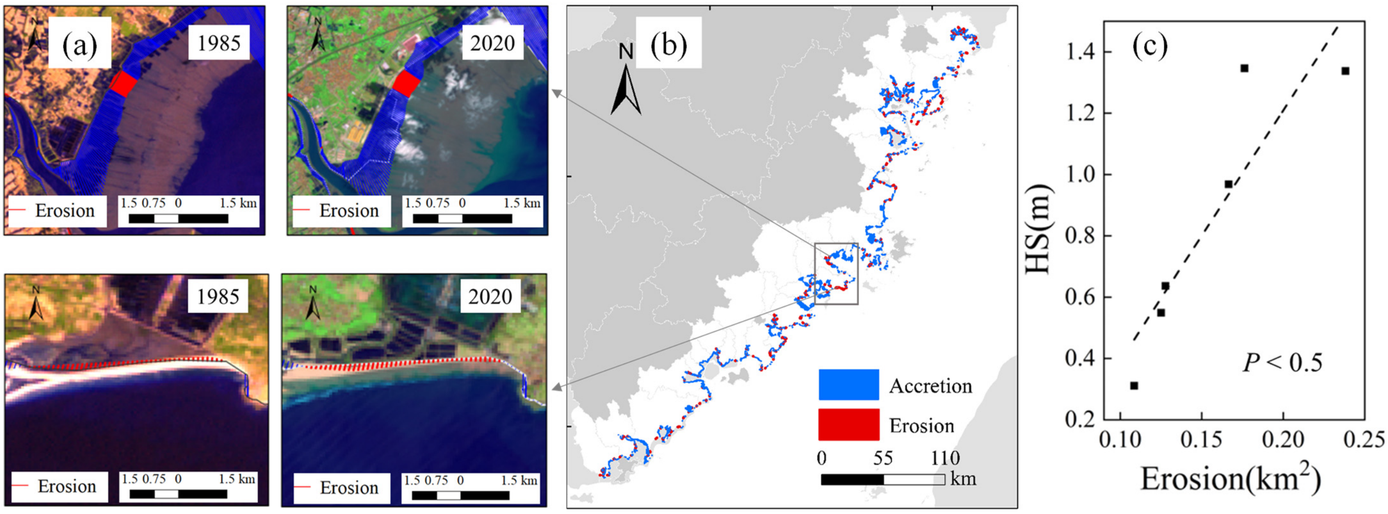


Figure 10. (**a**) Erosion and accretion of coastlines from 1985–2020; (**b**) The overview of Erosion of reclamation in continental coastlines of Fujian for 35years. (**c**) The relationship between erosion areas and local significant wave height.

There are two things notable in future coastal protection due to the changes in coastlines under rapid urbanization. On one hand, with the rapid expansion of urban areas represented by increased urban coastlines and land accretion (Figures 3 and 5), coastal cities are facing severe situations to cope with coastal disasters under climate change. The maintenance fee of hard infrastructures for coastal protection will cost more than before since the higher frequency and intensity of extreme meteorological events [33,34], such as storm surges, etc. On the other hand, the stronger local hydrodynamics induced by the sea-level rise will aggravate coastal erosion (Figure 10) [35]. Recently, the conceptions of the managed retreat and the living shoreline have become popular in many developed coastal countries for buffering the coastal communities [36,37]. For the developing coastal countries, more studies are required to be conducted to find an eclectic solution for the trade-off between economic development and coastal protection.

6. Conclusions

In this study, an integrated assessment framework was proposed to map the provincial and county-level spatiotemporal dynamics of continental coastlines and to explore drivers of coastline changes in the Fujian Province over the period from 1985 to 2020. The continental coastlines in the Fujian Province experienced a significant change in length, position, composition, and anthropogenic utilization over the past decades owing to rapid urbanization and economic development. Results showed that the total length of coastlines decreased first and then increased due to the different patterns of economic development. With the increasing impacts of human activities in coastal zones, the proportion of artificial coastlines and *ICUD* increased rapidly during the same period. Moreover, the seaward movement of coastlines due to the many reclamation projects resulted in a considerable increment in land areas. The pressure brought by the continuous concentration of population, urban areas, and industrial districts, is the primary factor that increased the degree of anthropogenic disturbances in the coastal zone. In addition, the policies issued by the local or central government can be critical tipping points for coastline changes in different periods. In general, our results demonstrated that the changes in the coastlines could be used as a proxy to assess the conditions of social-economic development in the coastal zone.

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