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Spatial-Temporal Analysis of the Coastline Changes in Fujian Province, China from 1995 to 2015

ABSTRACT

Coastline is the connection line between the land and the sea, and its extraction and analysis are of great significance to the coastal zone resources and environmental protection. Using remote sensing and Geographic Information Sysytem (GIS), coastline change from 1995 to 2015 in the Fujian Province, China, was extracted. The temporal and spatial evolution characteristics of coastline length, type and spatial location in the Fujian Province, China were analyzed. The coastline length continued to increase from 1995.29 km to 3555.036 km. The overall change intensity in 2010-2015 was the highest, reaching 0.87%, followed by 1995-2000. The smallest change occurred in 2005-2010. Based on the intensity changes in the six coastal cities of Fujian Province, Zhangzhou City showed the strongest coastline change. Except for the stability in 2000-2005, the changes that occurred during other years were larger. Fuzhou is the city with the smallest coastline changes, which have remained balanced for 25 years. Overall, the length of the rocky coastline and the sandy coastline generally show a downward trend, while the artificial coastline and the muddy coastline generally show an upward trend.

Keywords: *coastline, spatial-temporal analysis, remote sensing monitoring, Fujian Province*

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INTRODUCTION

Coastline is defined as the line between water and land (*Rachel 2012*). It is one of the fastest changing landscapes in the Earth's coastal regions (*Alesheikh et al. 2017, Manoj et al 2015, Sheik 2011*). Coastline is not only the boundary between water and land in coastal areas, but also contains a lot of environmental information. Change of a coastline will directly affect the coastal zone environment, which will affect a series of changes, such as coastal zone resources and ecology (*Goncalves et al. 2019, Godwyn-Paulson et al. 2020*). In recent years, artificial coastline changes, such as enclosing seas, cultivation and sea reclamation have increased (*Chen et al 2017, Santos et al. 2021*), which has led to increasing environmental pressures on land resources and the development of coastal zones (*Daoudi and Niang 2021*). There is an expansion trend of artificial coastlines, resulting in a steady decline in the proportion of natural coastlines (*Morhange 2000, Cawthra 2016*). Simultaneously, natural factors such as erosion and sedimentation caused by currents and waves, as well as rising sea levels, reduce the stability of the coast. Since the 1940s, due to increasing human activities, such as land reclamation and sea-farming, the coastline of mainland China has shown a significant artificial change, with over 68% of the coast advancing seaward and the land area increasing by nearly 14,200 km^2 (*Hou et al. 2016*). The changes in the coastline may have a direct impact on the distribution of intertidal mudflat area, resources distribution and wetland ecosystems, which in turn lead to changes in the coastal zone environment (*Chen et al. 2017*). However, the changes in the coastline of Fujian Province are particularly prominent. In recent years, coastal development activities, such as ports and fisheries, have been increasing, which inevitably affected coastline changes, Fujian Province one of the hot spots for coastline research in recent years. Therefore, accurately understanding the coastline changes in Fujian Province is of great significance for marine resource environmental protection and utilization in Fujian Province, China.

Satellite remote sensing images have the advantages of high precision and large-area monitoring. The dynamic changes in the coastline can be accurately monitored by satellite remote sensing images (*Bagaria et al. 2021, Wu et al. 2021, Dereli and Tercan 2020*). The coastline extraction method based on satellite remote sensing images is mainly divided into visual interpretation and computer automatic extraction methods. The traditional coastline visual interpretation method mainly extracts the coastline by artificial means. Visual interpretation is very laborious and time-consuming. Many scholars have studied automatic extraction method of coastlines. Based on 1976-2014 Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) images, *Wang* (*2019*) combined remote sensing image automatic classification with visual interpretation to extract coastlines. The spatial-temporal changes in the Yellow River Delta coastline were analyzed (*Wang 2019*). *Saleem and Awange* (*2019*) extracted the Liberia and Somalia coastlines based on high-time Sentinel-2. *Han* (*2019*) analyzed the temporal and spatial evolution characteristics of the Sanmen Gorge in China over the past 50 years by using remote sensing images, water depth data, and historical coastline data. Based on the tasseled cap transformation, the coastline of China's Yangtze River Estuary was extracted. Among the many automatic methods for extracting coastlines, the Normalized Difference Water Index (NDWI), which uses the band calculation to highlight the information of water bodies, is often used for coastline extractions (*Chen et al. 2019*). Water body extraction is carried out by the NDWI index. Thus, the water body and the land are effectively separated (*Mcfeeters 1996; Wang et al. 2017*).

The study aims to analyze the changes in the coastline of Fujian Province over the past 20 years by utilizing Landsat images from 1995 to 2015 and employing NDWI to extract the water body.

MATERIALS AND METHOD

Overview of the Research Area

The research area, with a total land area of 53.24 million km^2 and sea area of 13.6 km^2, is the junction of six coastal cities and the sea in the Fujian Province. It is located on the southeastern part of China, with Shaying Port in the north, Datun Bay in the south, and the East China Sea and Taiwan Strait on the right (**Figure 1**). The geographic coordinates are between

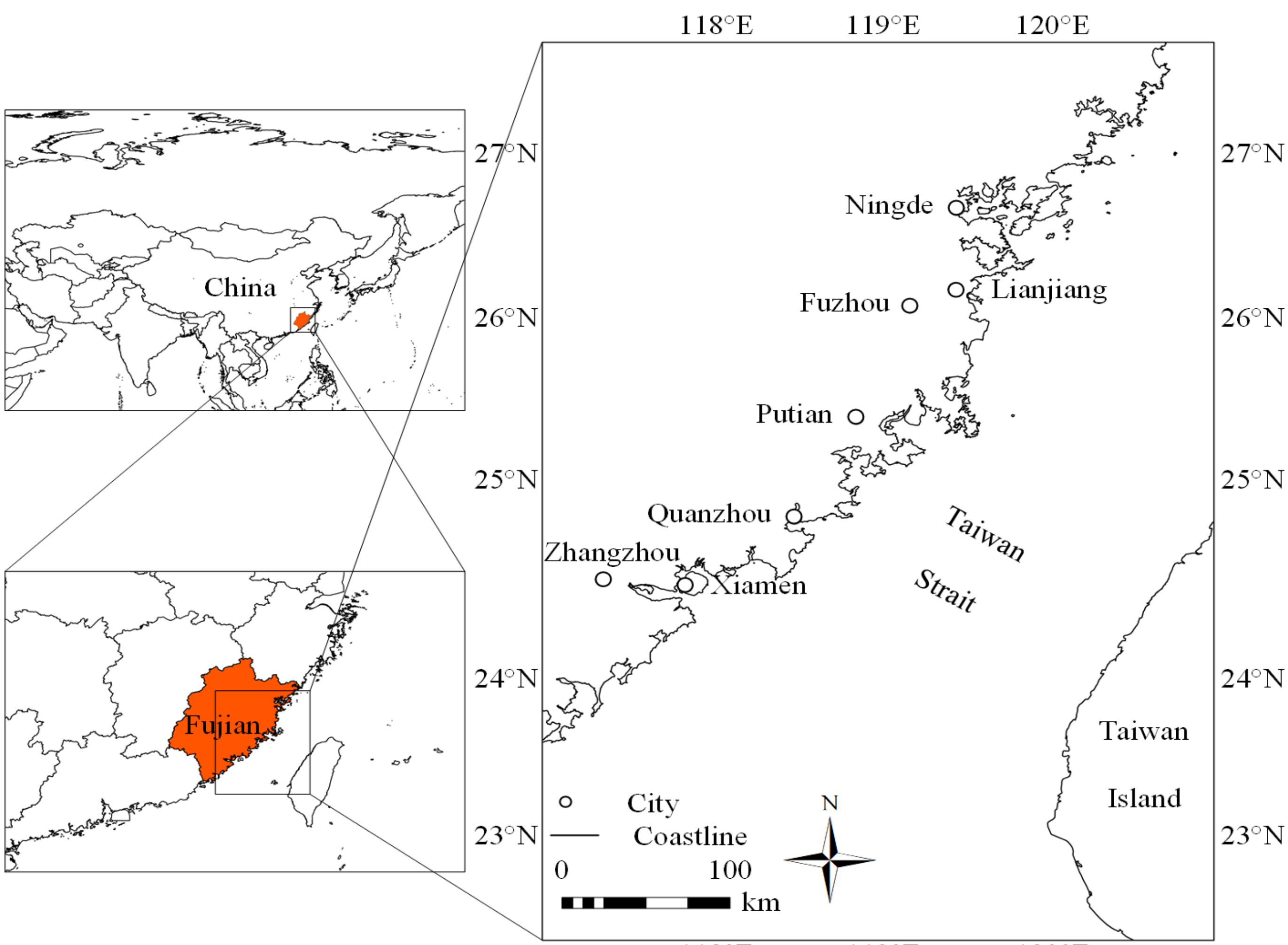

Figure 1. Location of the study area in Fujian Province, China.

23°33′50″ N~27°10′21″ N, 117°20′9″ E~120°26′20″ E. In recent years, the coastal zone of Fujian Province has been increasing in terms of sea-farming and land reclamation, and the rate of coastline change under anthropogenic influence has hastened. The study of the spatial and temporal change process of the coastline has a strong practical significance for the rational development and utilization of coastline resources and the sustainable development of ecological environment in Fujian Province, China.

Data Source

Landsat imageries of six coastal cities in the Fujian Province from 1995 to 2015 were downloaded from the United States Geological Survey website (http://glovis.usgs.gov). The images of 1995, 2000, 2005, 2010, and 2015 with image resolution of 30 m were selected.

Coastline Extraction Method

Coastline is the dividing line between the sea and land, referring to the average high tide level at the land and sea boundary (*Kar et al. 2021*). However, this trace is difficult to extract from remote sensing images. Therefore, the extracted coastline in this study is the boundary between the ocean and land. This boundary is called the waterside line. Based on the characteristics of the coastline, the coastline is divided into different types, including the rocky coastline, sandy coastline, muddy coastline, biological coastline and artificial coastline. Different types of coastlines use different remote sensing extraction rules:

Rocky coastline. The rocky coastline is defined by a prominent sea horn or an icy boundary between a steep cliff and the ocean.

Sandy coastline. The tidal water transport effect is deposited on the beach into a ridge-like sandy sedimentary belt. The sandy sedimentary belt is approximately parallel to the coast. The shoal ridge is taken as the sandy coastline.

Muddy coastline. The vegetation growing on the tidal flat along the outer boundary of the seaside is the muddy coastline.

Biological coastline. The location of the inner boundary of vegetation, such as mangroves or reeds, is defined as the biological coastline.

Artificial coastline. Materials such as stone and cement are used to construct coastlines surrounded by artificial buildings such as dykes, anti-waves and piers.

Because of no obvious biological coastline in the Fujian Province, the coastline of Fujian Province is divided into four types: rocky coastline, sandy coastline, muddy coastline and artificial coastline.

Normalized Difference Water Index (NDWI) is a classification method proposed by *McFeeters* (*1996*) based on the ratio between bands, and the main purpose is to extract water body information (*Gao 1996*). The method weakens the brightness values of vegetation and soil to a certain extent, thus facilitating the extraction of water body boundaries (*McFeeters 1996*). The NDWI calculation expression (Equation 1) is used to automatically extract the water body. Artificial interpretation is used to optimize the water boundary.

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (1)$$

Where, Green is the green band and NIR is the near-infrared band.

The water body’s reflectivity in the near-infrared band is close to zero, but the water body has a strong reflectivity in the green band. Hence, water image extracted by NDWI is brightly colored. Whereas, the reflection of vegetation is stronger in the near-infrared hence, dark color in the water image. After extracting the water body by NDWI and combined with visual interpretation, the spatial distribution of the different types of coastlines from 1995 to 2015 was extracted.

Spatial-temporal Evolution Analysis Method for the Coastline

Coastline change intensity. The variation intensity in the coastline length can be used to measure the difference in the variation rate of coastline length over a period of time (*Xu et al. 2013*). This value can express the annual average change in the coastline length within a certain period of time (Equation 2):

$$K_i = \frac{L_{iT2} - L_{iT1}}{L_{iT1}} \times \frac{1}{T_2 - T_1} \times 100\% \quad (2)$$

Where, K_i is the variation intensity of the coastline length from the T_1 year to the T_2 year; L_{iT1} and L_{iT2} are the coastline lengths from T_1 to T_2, respectively.

Coastline type structure variation. The coastline type structure variation characterizes the proportional relationship between different types of coastlines at a certain time (*Xu et al. 2013*) (Equation 3).

$$T_i = \frac{L_i}{\sum_{i=1}^{n} L_i} \times 100\% \tag{3}$$

Where, T_i is the proportion of the *i*-th coastline in a certain year, L_i is the coastline length of this type, and *n* is the number of coastline types. In this study, the coastline type is divided into four categories, and so $n = 4$.

RESULTS AND DISCUSSIONS

Analysis of Coastline Length Variation

Changes in the total length of coastline in Fujian Province. The total length of the coastline in the Fujian Province from 1995 to 2015 increased from 3,316.829 to 3,555.036 km (**Table 1 and Figure 2**). The coastline increased by 65.612 km in 1995-2000, 27.306 km in 2000-2005, 18.761 km in 2005-2010, and 149.064 km in 2010-2015. Zhangzhou City showed the largest change in coastline length, with an increase of 238.207 km from 1995 to 2015.

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The overall coastline change intensity in Fujian Province was the highest in 2010-2015, reaching 0.87%, followed by 1995-2000, and the smallest change in 2005-2010 (**Table 2**).

Based on the intensity of coastline changes in the six coastal cities, the City of Zhangzhou showed the biggest change. Except for the stability in 2000-2005, the changes during other years are larger. Fuzhou is the city with the smallest changes in coastline. During the 20-year period, the coastline changes remained balanced.

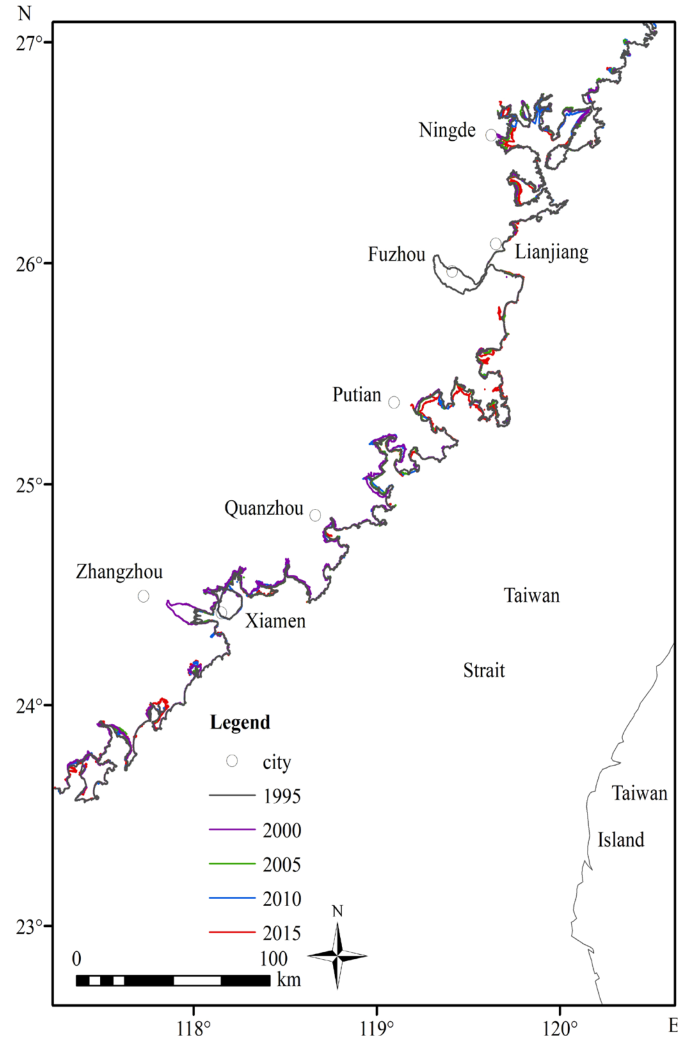


Figure 2. Changes in the coastline of the Fujian Province, China from 1995 to 2015.

Change in coastline length in Ningde. The length of the coastline in the city of Ningde was 946.355 km in 2015, a decrease of 28.343 km compared with 1995 (**Figure 4**). In particular, the changes from 2000 to 2005 and from 2005

Table 1. Total length of coastline in Fujian Province and the coastline length of each coastal city (km).

Years	Ningde	Fuzhou	Putian	Quanzhou	Xiamen	Zhangzhou	Total Length
1995	974.698	884.509	245.179	388.757	232.508	591.178	3316.829
2000	940.514	882.932	248.274	421.569	239.449	649.703	3382.441
2005	996.114	856.773	251.064	408.727	247.662	649.407	3409.747
2010	952.345	853.169	255.135	420.890	240.944	683.489	3405.972
2015	946.355	863.519	262.198	431.641	252.628	798.695	3555.036

Table 2. The intensity of coastline changes in the Fujian Province and the intensity of coastline changes in coastal cities (%).

Years	Ningde	Fuzhou	Putian	Quanzhou	Xiamen	Zhangzhou	Total Length
1995-2000	-0.70	-0.04	0.25	1.69	0.60	1.98	0.40
2000-2005	1.18	-0.59	0.22	-0.61	0.69	-0.01	0.16
2005-2010	-0.88	-0.08	0.32	0.60	-0.54	1.05	-0.02
2010-2015	-0.13	0.24	0.55	0.51	0.97	3.37	0.87

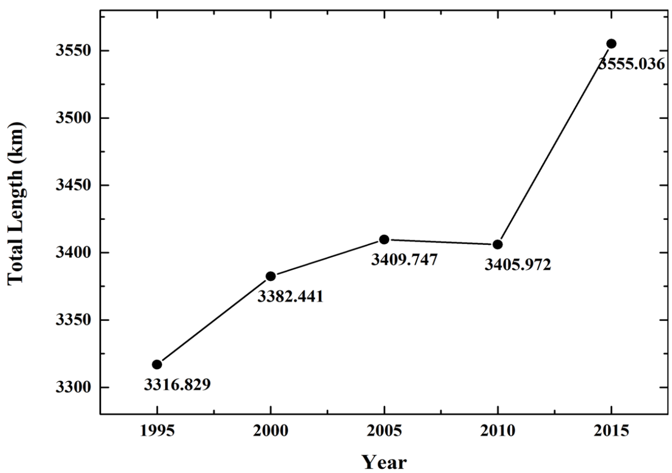


Figure 3. The overall length change of Fujian Province coastline in China.

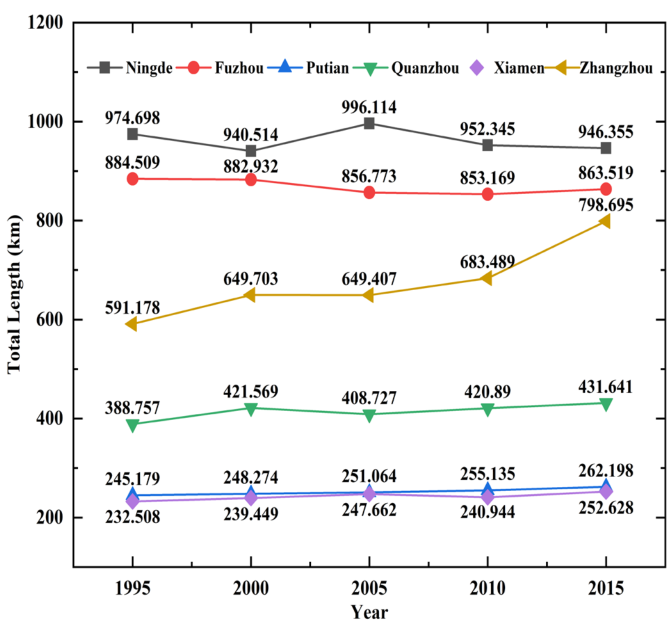


Figure 4. The coastline length change of each coastal city of Fujian Province, China from 1995 to 2015.

to 2010 were the most significant, with annual average change rates of 1.18% and -0.88%, respectively. During this period, the changes were mainly due to the deposition of sand around Sansha Bay and the development of marine aquaculture and tidal flat reclamation.

Change in coastline length in the city of Fuzhou. The length of the coastline in Fuzhou was 863.519 km in 2015, a decrease of 20.99 km compared with 1995 (**Figure 4**). The most significant increase was the period from 2000 to 2005, with a decrease of 26.159 km and an annual average rate of -0.59%. The main change is the outward movement of the Luoyuan Coastline Bay, which made the coastline smooth with no twists or turns. The coastline length increased by 10.35 km from 2010 to 2015, due to the increase in the tortuosity of the Minjiang Estuary and Luoyuan Bay coastlines.

Changes in coastline length in the city of Putian. The length of the coastline in the City of Putian was 262.198 km in 2015, an increase of 17.019 km compared with 1995 (**Figure 4**). The overall change in the City of Putian is not significant and the annual average rate of change is approximately 0.34%, showing an upward trend.

Changes in the length of the coastline in Quanzhou. The length of the coastline in the City of Quanzhou was 431.641 km in 2015, an increase of 42.884 km compared with 1995 (**Figure 4**). The length of the coastline in Quanzhou is mainly increasing. However, from 2000 to 2005, it decreased by 12.842 km, and the annual average rate of change was -0.61%. The amount of sediment discharged in Jinjiang has become so large that the sediments in Quanzhou Bay and the sediments from seawater, as well as the construction of artificial buildings such as dams have reduced the tortuosity of the coastline of Meizhou Bay.

Changes in coastline length in Xiamen City. The length of the coastline in Xiamen was 252.628 km in 2015, an increase of 20.12 km compared with 1995 (**Figure 4**). Overall, the coastline is increasing, but it decreased by 6.718 km between 2005 and 2010. Any major changes in the muddy coastline are slowed down by twists and turns.

Change in coastline length in the City of Zhangzhou. The length of the coastline in the City of Zhangzhou was 798.65 km in 2015, an increase of 207.517 km compared with 1995 (**Figure 4**). From 1995 to 2015, the coastline of the City of Zhangzhou was observed to have an increasing trend from1995 to 2015.

The coastline moved inward from 1995 to 2000, due to the reduction in sandstone deposits in the Longjiang Estuary. The degree of tortuosity increased significantly, which increased its length by 58.525 km. From 2010 to 2015, the coastline increased by 115.206 km, with 3.37% annual average rate of change. The main changes seen in the sandy coastline of Futouwan and Dongshan Bay were washing and erosion by tidal currents and waves, due to the coastline to move inward and become smooth and curved. In recent years, as a coastal city in the Fujian Province, the city's economic development has become better, which led to its rapid expansion, and human activities such as the construction of dikes around the sea are becoming increasingly denser.

The Coastline Structure Changes in Fujian Province

Overall changes in coastline types in the Fujian Province. The lengths of the rocky and the sandy coastline generally showed a downward trend, while the artificial coastline and muddy coastline generally showed an upward trend (**Tables 3 and 4**). The period of maximum variation in the rocky coastline was 2000-2005, which was reduced by 246.062 km, and the rate of change was 7.89%. The largest change in the artificial coastline occurred from 2005 to 2010, with an increase of 117.556 km and a rate of change of 3.50%. The greatest change in the quality of the coastline occurred from 2005 to 2010, with a reduction of 152.852 km and a rate of change of 4.38%. The greatest change in the muddy coastline occurred from 2000 to 2005, with an increase of 287.234 km and a rate of change of 8.15%.

The continuous growth of the artificial coastline indicated the increase of coastal development activities, especially the artificial coastline growth of about 150 km in the last 10 years. This is mainly reflected in human reclamation, land reclamation, port construction, and fishery facilities construction.

The shortening of the rocky coastline is not due to coastal erosion, but also from beach reclamation, which makes the rocky coastline enclosed within the artificial coastline. Estuarine erosion and sedimentation have increased the length of the muddy coastline every year.

The total length of the coastline increased by 219.845 km between 1995 and 2015, mainly showing a significant increase in the degree of coastline twists and the movement of coastlines in some areas. The remote sensing interpretation results showed that the factors affecting the coastlines change from 1995-2015 were mainly composed of natural and human factors (**Figure 5**).

The natural factors were mainly estuarine erosion and sedimentation. Sedimentation had the greatest impact, while other natural factors, such as seawater erosion and global warming caused a smaller degree of coastlines change.

The human factors mainly include human reclamation, land reclamation, port construction, fishery and facilities construction, which made the coastline become flat and the coastline expand outward. The trend of coastline expansion was mainly in three aspects: Fujian is a large marine province, and the rapid development of marine economy in the Province in the past decade. Although port construction can drive the economic growth of coastal areas, the construction work will inevitably lead to the change of coastline; the farming and fishing industries in coastal areas are also more developed and large areas of polder and a large

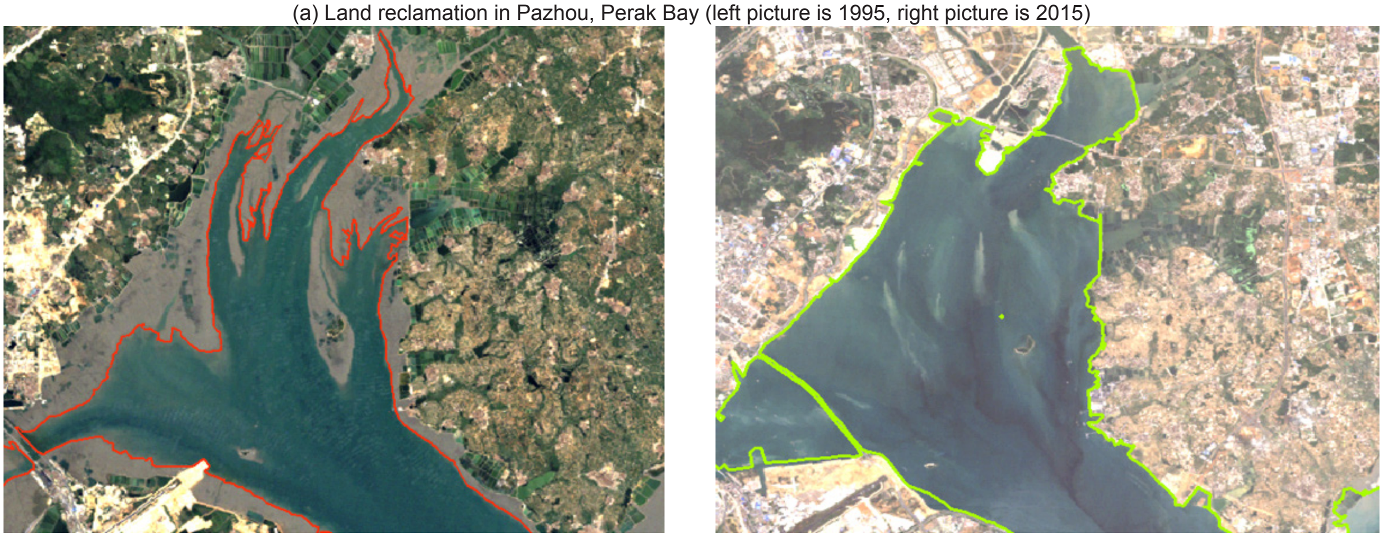
Table 3. Coastline lengths of different coastline types in Fujian, China from 1995-2015.

Years	Rocky Coastline	Sandy Coastline	Muddy Coastline	Artificial Coastline
1995	1,871.827	603.881	710.436	130.685
2000	1,939.226	622.798	649.546	170.871
2005	1,693.164	585.819	936.780	208.970
2010	1,696.881	432.967	945.599	326.526
2015	1,632.743	506.040	1065.59	350.663

Table 4. Rate of change in different coastline types in Fujian, China from 1995-2015.

Years	Rocky Coastline	Sandy Coastline	Muddy Coastline	Artificial Coastline
1995-2000	0.90	0.21	-2.22	1.11
2000-2005	-7.89	-1.31	8.15	1.05
2005-2010	0.44	-4.38	0.44	3.50
2010-2015	-3.95	1.51	2.18	0.27

(a) Land reclamation in Pazhou, Perak Bay (left picture is 1995, right picture is 2015)



(b) Seawater erosion near the Xiang'an District, Xiamen (left picture is 1995, right picture is 2010)

Figure 5. Distribution of coastlines in the Fujian Province, China from 1995 to 2015.

number of artificial sea walls have become inevitable products, which also cause changes in the coastline; and due to economic development, population increase and housing area increase, the coastal areas had to be enclosed to alleviate the situation of land tension, among which Xiamen, Quanzhou and Putian are the most serious land enclosure.

Although large-scale marine engineering construction has increased marine economic output and adapted to urban development needs in the short term, it has had a huge impact on the local environment (*Wang et al 2016*), mainly in the following three aspects: as can be seen from the trend of changes in coastline types, the length of artificial coastline has increased by about 150 km in the past 10 years, and the natural coastline has been declining, which not only reduces the ecological function and resource value of the coastline, but also causes significant changes in both sea and land interactions in the coastal zone; the reduction of water area will cause the erosion and deposition of the Bay and the change of landform; and the construction of marine engineering will lead to a sharp decrease in marine biodiversity.

CONCLUSIONS AND RECOMMENDATIONS

Based on remote sensing imagery, the coastline of Fujian Province in China from 1995 to 2015 was extracted. The spatial and temporal changes in the coastline were analyzed. In 1995-2015, the length of the coastline increased significantly, especially during 1995-2000 and 2010-2015. The coastline variation showed a continuous increasing trend from 1995 to 2015, with the coastal cities in the order of Zhangzhou, Xiamen, Putian, Quanzhou, Fuzhou, and Ningde. Human activities have changed the ratio between different types of coastlines, as reflected in the overall decreasing trend of the rocky and the sandy coastline, and the overall increasing trend of artificial coastline and muddy coastline. The corresponding human activities were mainly human reclamation, land reclamation, port construction and fishery facilities construction; and although the construction of marine engineering increased the output value of marine economy and adapted to the demand of urban development in the short term, it has a negative impact on the local environment.

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