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Analysis on the Dynamics of Coastline and Reclamation in Pearl River Estuary in China for Nearly Last Half Century

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Abstract: The Pearl River Estuary is in the geometric center of Guangdong-Hong Kong-Macao Greater Bay Area, which is one of the main battlefields to drive the high-quality development of China's economy. This paper uses seven sets of typical satellite images in Pearl River Estuary for nearly half a century (from 1973 to 2021) to analyze the changes of coastline and sea reclamation. The results show that from 1973 to 2021, the total length of the coastline of the Pearl River Estuary increased from 240.09 km to 416.00 km, and that of the continental coastline from 186.87 km to 246.21 km (but the length of natural coastline in the continental coastline decreased from 136.91 km to 15.17 km). In the same period, the total reclamation area of the Pearl River Estuary increased by 28,256.06 ha. Before 2012, the growth rate of reclamation was generally fast. After 2012, the reclamation in China has entered a period of reflection. With reclamation was strictly controlled in the new era, only the previously approved reclamation projects and national major projects have been guaranteed, which makes the average annual growth rate of the coastline length and the reclamation area in the region show a significant downward trend. The reclamation in early days was largely for agriculture and pond culture purposes, but is shifting to transportation, industrial development, and urban construction in recent decades. This study scientifically analyzes the coastline and reclamation changes of the Pearl River Estuary in the past half century, which has a very important reference value for the next step to formulate marine ecological protection and restoration strategies, and construct a new pattern of marine space development and protection.

Keywords: Guangdong-Hong Kong-Macao Greater Bay Area; coastline; sea reclamation; Pearl River Estuary; change analysis

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1. Introduction

China is one of the earliest countries in history to start sea reclamation, which is a way for humans to ask for production and living space from the ocean. Though having expanded space for human activity, it has seriously affected the offshore environment, resulting in narrowed marine ecological space, impaired functions of ecosystems, lowered biodiversity, polluted water bodies, and weakened disaster prevention and reduction capabilities [1–12]. The natural shorelines formed by the interaction between land and sea are unique, highly valuable, and irreplaceable natural resources. They are scarce, extremely important, and difficult to regenerate. Natural coastlines and coastal wetlands are important ecological spaces, key habitats and breeding grounds for marine organisms, and the transfer point for birds in migration, which are high in biodiversity and valuable in underpinning ecological security. Natural coastlines can effectively resist extreme ocean disasters such as typhoons and storm surges, and provide beautiful scenery and spaces for humans to be close to the ocean. Like many countries in the world, while the reclamation promoted local economic development in China, it has also shortened the retention rate of natural coastlines.

The Guangdong-Hong Kong-Macao Greater Bay Area (GBA for short) which covers the Hong Kong Special Administrative Region of China; Macau Special Administrative Region; and nine prefecture-level cities of Guangdong Province including Guangzhou, Shenzhen, and Zhuhai, is one of the most open-oriented regions of the strongest growth vitality in China. It is also a key space area for China to achieve high-quality growth and sharper global competitiveness. The Pearl River Estuary is located in the geometric center of the GBA. The changes in its marine resources and their spatial distribution, especially in the temporal and spatial changes of marine ecological space and development and utilization space, are having a huge impact on the economic, social, and ecological environment of the GBA. The Province of Guangdong, home to the Pearl River Estuary, is highly representative in coastline and sea reclamation as it has experienced different reclamation stages for land resources, e.g., for the purposes of agriculture, pond culture, port construction, industrial development, and urbanization [13]. Coastal evolution is a dynamic and continuous process which mirrors the strength of the combined effects of nature, economy, and society. The coastline, at the front of coast–ocean interaction, is in dynamic changes all the time. Coastal changes are primarily driven by natural and human factors, while the former has been historically dominant, and the latter took on the role only in recent decades [14–17].

More and more human activities are constantly touching the boundary and bottom line of natural ecology, which is an ecosystem free from human influence or intervention. Analyzing the changes of coastline and reclamation is of great significance to protect shoreline and tidal flat resources, study the balance and stability of ecosystems, reasonably limit the spatial scope of economic and social activities, better understand the development trend of the life community of man and nature, and promote the sustainable development of coastal zones. Traditional surveys on coastline and reclamation were largely on-site exploration, positioning, and desk-top mapping analysis, which is very energy- and time consuming. A remote sensing image is rich in spectral information and can directly reflect the distribution features of the coastline. A comparison and analysis of the images of different time phases can present the overall picture of the law of change of the coastline and the causes behind it. Remote sensing is frequently used in recent years to extract the data of rivers, islands, and bay shorelines, and analyze the changes of erosion, scouring and silting, and the driving factors behind them, with already many successful cases [18–33].

Since the launch of Landsat in 1972, the National Aeronautics and Space Administration of the United States (NASA) has acquired a great amount of satellite remote sensing data, which are accessible for free online. With seven sets of typical imageries of the Pearl River Estuary pictured by NASA's Landsat TM/ETM+/OLI sensors during 1973–2021 as the source data, this paper extracted coastlines of Chinese mainland and different islands and analyzed the evolution process, structure features, and driving factors of reclamation. The analysis of the series data spanning nearly half a century presents the historical changes of the coastline and reclamation of the Pearl River Estuary in an objective and straightforward way. It can serve as a valuable reference to the sustainable utilization of the local coastline and coastal wetland, better and more efficient marine resource protection and utilization, tightened control of the use of the territorial space of GBA, optimal layout, and more coordinated regional development.

2. Study Area

The Pearl River is the second largest (in terms of runoff) and the fourth longest river in China [34]. Located in the lower reaches of the Pearl River in south-central Guangdong and bordering the South China Sea, the Pearl River Delta is a complex region formed by various depositions of the sediments at the estuary from the Pearl River system. Surrounded by the natural barriers of hills and mountains in the west, north, and east, with a long coastline in the south, it has a subtropical ocean monsoon climate bringing about abundant rainfall in April–September and sufficient heat. Northerly wind prevails in winter and the weather is dry [35]. Summer is hot and rainy with southwest and southeast wind. The national first-class protected animal *Sousa chinensis* (Indo-Pacific humpback dolphin) and second-class protected animal *Bahaba taipingensis* (Chinese bahaba) are distributed here [36,37].

The rivers flowing into the Pearl River Delta are high in runoff volume and sediment concentration. The typical morphological characteristics of the study area are islands near distributary river mouths, with large underwater topographic changes [38]. The waves in this bay are too small to affect the coastline [39]. The tidal range is small (the average tidal range is between 0.86–1.69 m), which on the east bank is averagely greater than that on the west bank. Generally, the velocity of ebb tide is greater than that of flood tide, and the velocity of the surface layer is greater than that of the bottom layer [40]. Blocked by the underwater shoals and many islands around, the coast is already silted to a certain extent, and the riverbed is slowly silting up with irregular half-day tide. This water area underpins the development of the Pearl River Delta as the reclamation on the tidal flats provides sufficient land resources for industrial and urban development. However, the size of tidal flat areas has been shrinking dramatically and the natural shoreline suffered a sharp cutoff which further affected the marine ecosystem.

The water resources in the Pearl River Delta are abundant with a river network density of 0.8 km/km^2. Its crisscrossed and interconnected water network boasts more than 100 main river ways stretching out to about 1700 km. The rivers of Dongjiang, Xijiang, and Beijiang converge here and flow into the South China Sea through eight radially lined-up estuaries, including four in the east via which rivers flow into Lingdingyang. They are mostly known as the "East Four Estuaries", including the estuaries of Humen, Jiaomen, Hongqimen, and Hengmen. The study area of this paper is exactly the sea area surrounded by the "East Four Estuaries", with geographic coordinates ranging from 22°19′59″~22°48′19″ N, 113°31′58″~114°03′26″ E (Figure 1).

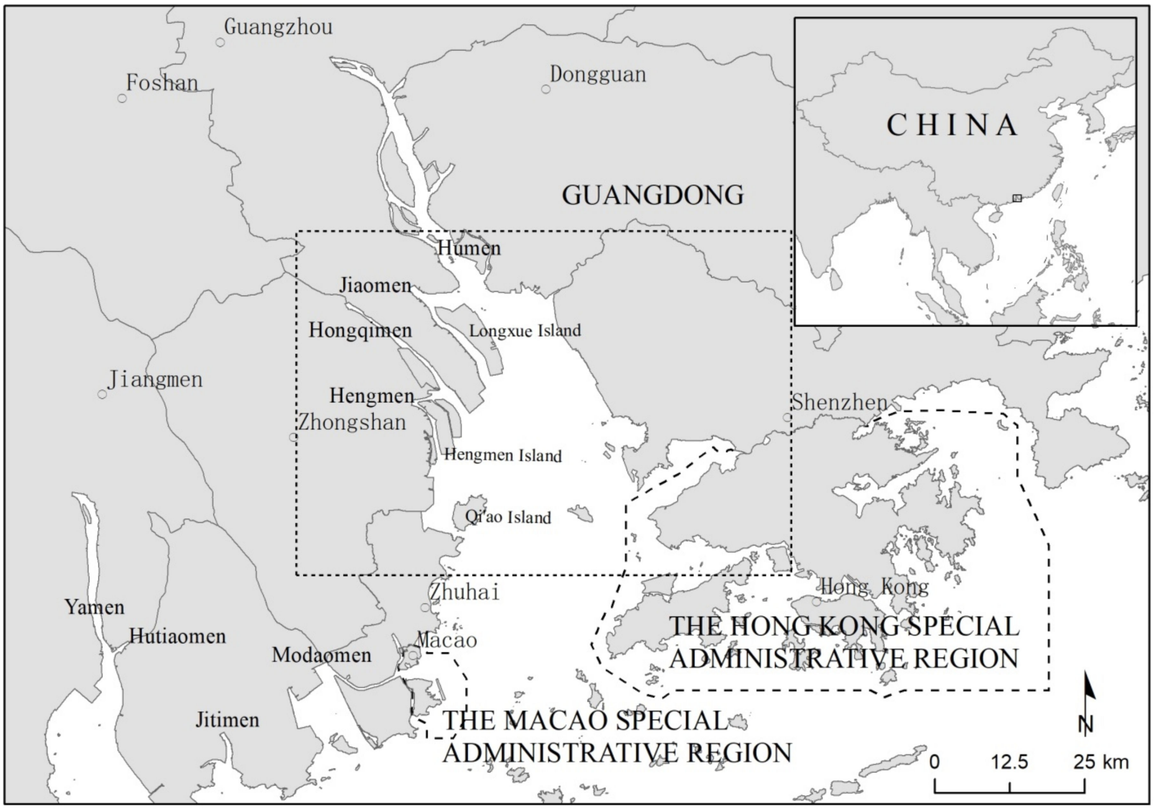

Figure 1. Map of geographical scope in the study area (dashed rectangle in the figure).

3. Materials and Methods

3.1. Data Sources

The satellite remote sensing data used in this study are available for free on the website of the United States Geological Survey (http://glovis.usgs.gov, accessed on 15 October 2021) and China Geospatial Data Cloud (http://www.gscloud.cn, accessed on 8 March 2021). Acquired in clear weather conditions, the images are all of high quality and good for interpretation and analysis. Table 1 shows the basic attributes of the satellite data in typical years in the study area, and Figure 2 presents the satellite remote sensing images used in this study.

Table 1. Basic Attributes of Satellite Data in Typical Years in the Study Area.

Number	Date Acquired	Spacecraft	Sensor	Path/Row	Maximum Ground Resolution
1	25 December 1973	Landsat 1	MSS	131/044	80 m
2	2 November 1978	Landsat 2	MSS	131/044	80 m
3	8 December 1987	Landsat 5	TM	122/044	30 m
4	24 October 1994	Landsat 5	TM	122/044	30 m
5	7 November 2002	Landsat 7	ETM	122/044	15 m
6	2 November 2012	Landsat 7	ETM	122/044	15 m
7	20 February 2021	Landsat 8	OLI	122/044	15 m

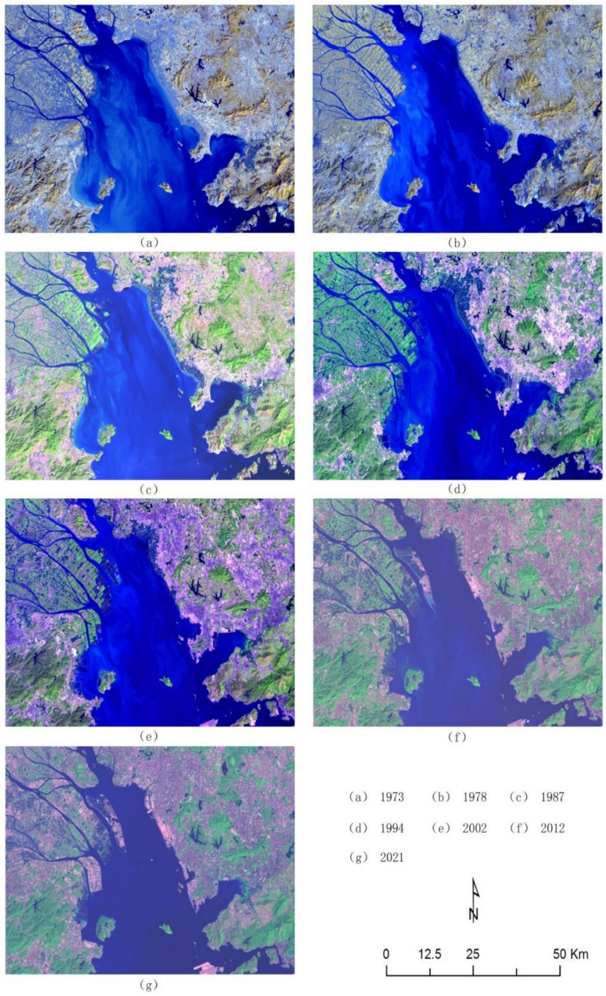

Figure 2. Satellite images in typical years in the study area (taken in 1973–2021). (**a**) 1973 remote sensed image; (**b**) 1978 remote sensed image; (**c**) 1987 remote sensed image; (**d**) 1994 remote sensed image; (**e**) 2002 remote sensed image; (**f**) 2012 remote sensed image; (**g**) 2021 remote sensed image.

The images chosen in this study are highly representative. In particular, the images of 1973, which were taken one year after the US launched Landsat, are the early images of the highest quality in the region. The year 1978 was the start of China's reform and opening-up. In 1987, the 13th National Congress of the Communist Party of China (CPC) put forward the policy of "One Center, Two Basic Points", namely "centering around economic development, adhering to the four cardinal principles, and being committed to reform and opening-up", which helped boost China's economy to a period of rapid development. In 1994, the State Council of China adopted the "China's Agenda 21" which identified a sustainable development strategy. The year 2002 was the first year when the "Law of the People's Republic of China on the Administration of the Use of Sea Areas" took effect, which ushered in the era of law-based management of the sea areas in China. In 2012, the 18th CPC National Congress incorporated ecological civilization into the overall layout of the socialism with Chinese characteristics and integrated it into the full endeavor of pursuing economic, political, cultural, and social progress, followed by the strict management and control of the coastline and sea reclamation. The above policies and plans are an important basis to coordinate and regulate various marine development activities, including sea use administration and marine conservation, that are highly relevant to the changes of the coastline and reclamation. This paper discusses the research in six important development stages.

3.2. Data Processing

The remote sensing images were first preprocessed with radiometric calibration and atmospheric correction followed by geometric correction on the images acquired on 7 November 2002 with national basic geographic information data at 1:50,000. The study then selected the feature points of the appropriate quantity and distribution areas to register other remote sensing images to unify the coordinate system and projection, and then performed a bands synthesis and enhancement processing. The processing method is not elaborated in detail here as it is already very mature [41] (Figure 3).

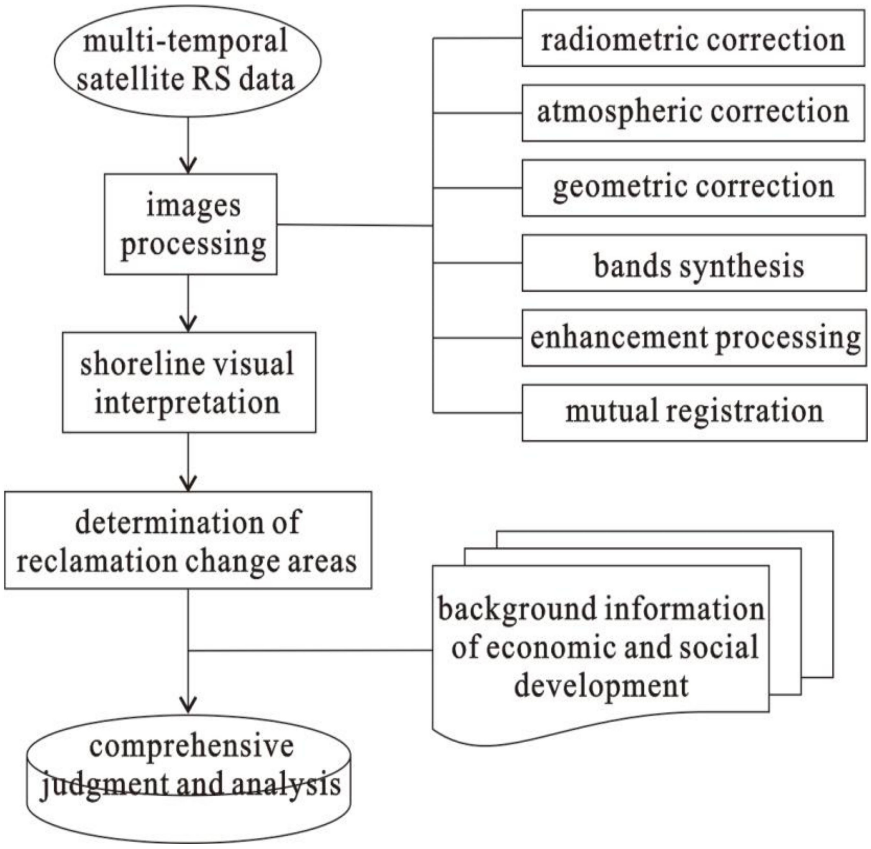

Figure 3. Flow chart of the methodology.

As the coastline is the land and water traces of the mean high-water spring, the instantaneous waterline extracted by remote sensing images cannot determine its location in strict sense. The coastline was defined at the outer edge of the top of the embankment above the tidal flat, rather than the land sea boundary at the moment of remote sensing image acquisition. At the same time, we also comprehensively compared, analyzed, and judged the on-the-spot surveyed coastline data released by the People's Government of Guangdong Province in 2008. Due to the low spatial resolution of satellite remote sensing images in the 1970s and 1980s, the types of coastlines were mainly determined by consulting old experts and local residents. The recent satellite remote sensing images have higher spatial resolution; with reference to the coastline survey data in 2008, the coastline type can be determined. This study obtained the coastline distribution data in multiple periods, extracted the distribution range of reclamation, and conducted an in-depth analysis of the coastline changes and the reclamation of the Pearl River Estuary in light of local socio-economic development (e.g., sea area and land ownership information, coastline renovation and restoration projects, relevant planning, etc.). For the island coastline, only the natural and artificial islands that experienced changes were analyzed. Finally, integrated national policies and regional development objectives comprehensively judged and analyzed the causes and extent of ecological degradation in the region, and the strategies to conserve the ecology of estuary and coastal resources were put forward.

4. Results

4.1. Analysis of the Coastline Changes in Length and Type

The coastline as a resource is extremely valuable and plays a unique role in ecological conservation. It is not only at the forefront of the opening-up and economic and social progress of coastal areas, but also the key barrier to guaranteeing national ecological security. Tables 2 and 3 show that though both witnessed an increasing trend during the study period, the island coastline had been growing significantly faster than that of the mainland. During the years between 1973 and 1978 before China's reform and opening-up, the total coastline grew very slowly, increasing only from 240.09 km to 244.71 km, at an average annual growth rate of 0.45 km/a for the mainland, and 0.49 km/a for the island. The stage spanning from 1978 to 1987 was a period of relatively fast growth with the total coastline increasing from 244.71 km to 274.00 km at 1.93 km/a annually for the mainland, and 1.30 km/a for the island. The years between 1987 and 1994 were a period of very fast growth when the total length increased from 274.00 km to 336.70 km at an average rate of 1.92 km/a annually for the mainland and 7.26 km/a for the island. The growth slowed down during 1994–2002 when the total length increased only from 336.70 km to 378.40 km with 1.73 km/a for the mainland and 3.42 km/a for the island. The coastline growth rate further slowed down from 2002 to 2012 with the total up from 378.40 km to 409.79 km, with 1.20 km/a for the mainland and 1.94 km/a for the island. It has continued to go downward since 2012, as the total length increased only from 409.79 km to 416.00 km with 0.06 km/a for the mainland and 0.69 km/a for the island. On the whole, the total length of the coastline in the region is still going up but has had a downturn year-on-year average annual growth rate since the 1990s.

Table 2. Statistics of mainland shoreline and island coastline in Pearl River Estuary (unit: km).

	1973	1978	1987	1994	2002	2012	2021
Mainland coastline	186.87	189.07	206.57	219.66	233.68	245.69	246.21
Island coastline	53.22	55.64	67.43	117.05	144.72	164.10	169.79
Total length	240.09	244.71	274.00	336.70	378.40	409.79	416.00

Table 3. Average annual growth of mainland shoreline and island coastline in Pearl River Estuary (unit: km/year).

	1973–1978	1978–1987	1987–1994	1994–2002	2002–2012	2012–2021
Mainland coastline	0.45	1.93	1.92	1.73	1.20	0.06
Island coastline	0.49	1.30	7.26	3.42	1.94	0.69

It can be seen from Table 4 that from 1973 to 2021, while the length of the artificial coastline increased from 49.96 km to 231.04 km, the natural coastline decreased from 136.91 km to 15.17 km. The artificial shoreline can be used for urban life and leisure tourism, the port and harbor industry, and dams for aquaculture and storm surges. In the 1970s, most of the artificial shorelines of the Pearl River Estuary were used for dams for the aquaculture industry and storm surge prevention, and then gradually shifted to urban life and leisure tourism, ports, and harbor industries.

Table 4. Statistics of different mainland shoreline types in Pearl River Estuary (unit: km).

	1973	**1978**	**1987**	**1994**	**2002**	**2012**	**2021**
Natural shoreline	136.91	125.03	85.99	46.02	27.01	24.72	15.17
Artificial shoreline	49.96	64.04	120.58	173.64	206.67	220.97	231.04
Total length	186.87	189.07	206.57	219.66	233.68	245.69	246.21

The main types of natural coastlines on the mainland are largely silty, biological, and bedrock coastlines, etc. In the 1970s, the natural coastlines on the mainland of Pearl River Estuary were mostly distributed in the west of Shenzhen, with simple earth embankments along the coast, and quite good tidal flats on the outside, which were gradually replaced by artificial structures such as strong seawalls and wharfs. Studies show that the natural coastline in this area has a continuous downward growing trend; however, for some artificial coastlines, after their renovation or long-term sea–land interaction, the outer beaches of the seawall gradually silted up, and once reaching a new dynamic balance of erosion and siltation, the intertidal zone would gradually restore their natural form and function. Such coastlines can be managed in the way of natural coastlines in the future.

4.2. Analysis of Reclamation Changes

It can be seen from Figure 4 to Figure 5 that in the past half century, the total area of reclamation in this region increased by 28,256.06 ha. The most significant changes happened in the east and west banks of the Pearl River Estuary as well as Longxue Island and Hengmen Island, with a huge impact on the form and topography of the coast of the estuaries of Jiaomen, Hongqimen, and Hengmen, etc.

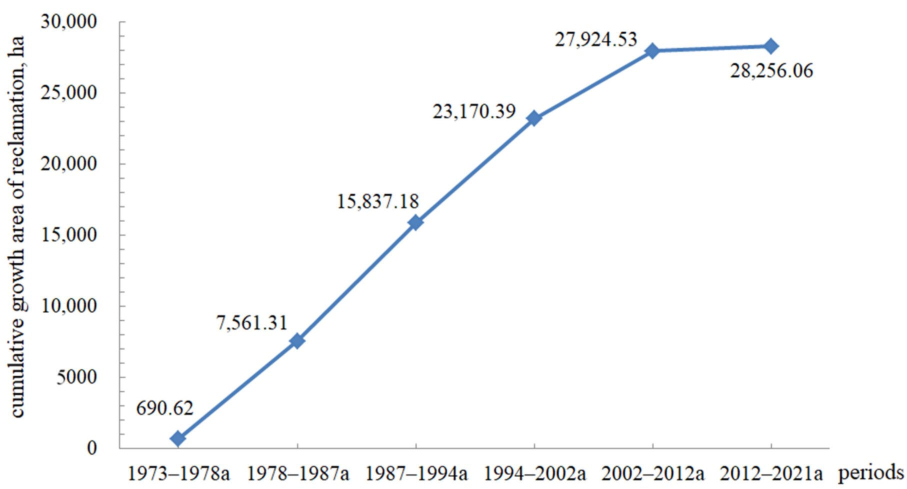

Figure 4. Growth of reclamation areas in Pearl River Estuary.

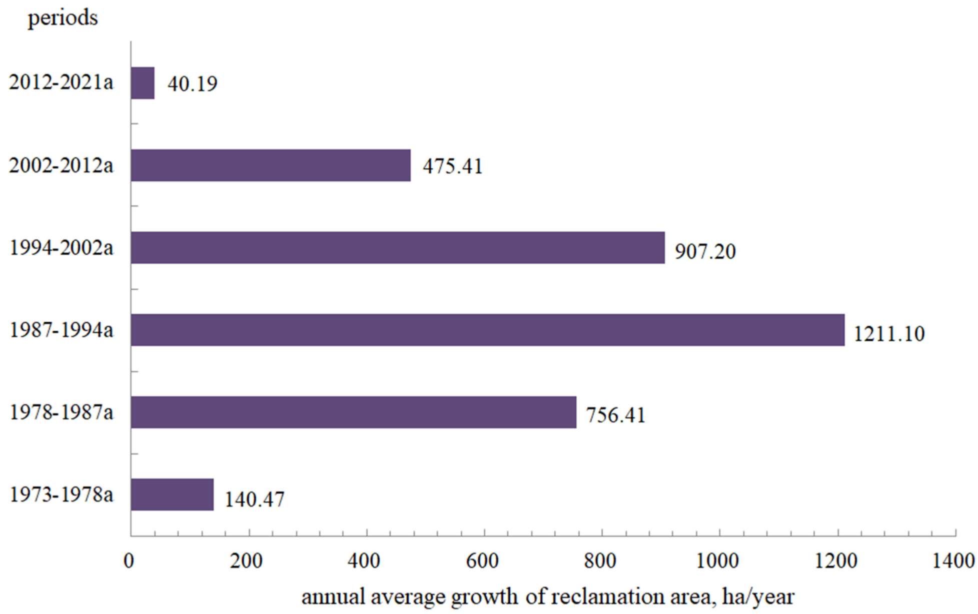

Figure 5. Average annual reclamation area.

The period spanning from 1973 to 1978 before China's reform and opening-up drive was a stage of slow growth of reclamation, as the total reclamation area in this period only increased by 690.62 ha, at an average annual growth rate of 140.47 ha/a, mainly in the southeast of Guangzhou and southwest of Shenzhen. Since the start of reform and opening-up from 1978 to 1987, the reclamation drive was in the fast lane with the total area up by 6870.69 ha at a rate of 756.41 ha/a, mainly in the coastal waters in southeast of Guangzhou, southern Dongguan, and western Shenzhen. From 1987, when the national policy of "centering on economic development" was proposed, to 1994, the reclamation efforts further accelerated at a rate of 1211.10 ha/a, which drove up the total area by 8275.86 ha, mainly in the southeast of Guangzhou and the coastal waters of Longxue Island, Zhongshan Hengmen Island, and northern Zhuhai. Since the sustainable development strategy was determined from 1994 to 2002, the growth of the reclamation projects slowed down with the total area up by 7333.21 ha at an average annual growth rate of 907.20 ha/a, mainly in the southeast of Guangzhou and coastal waters of Longxue Island, Zhongshan Hengmen Island, northern Zhuhai, and western Shenzhen. From 2002 when the *Law of the People's Republic of China on the Administration of Use of Sea Areas* was promulgated until 2012, the reclamation projects had further slowed down with only an increase of 4754.14 ha in its total area at an annual rate of 475.41 ha/a, mainly in the south of Longxue Island in Guangzhou and the coastal waters of western Shenzhen. In 2012, as the 18th CPC National Congress incorporated ecological civilization into the overall layout of "Five in One" for national development, ocean development and conservation also came into a phase of reflection as to how it should proceed. The review and approval process for the regional sea use and reclamation by individual projects has slowed down significantly. The management and control of reclamation was particularly tight in 2018 when the State Council issued the "*Notice on Strengthening Coastal Wetland Conservation and Sea Reclamation Management and Control*", which drove down the growth rate of reclamation projects. The new projects are mostly well-prepared and ready for construction. The total area of reclamation increased by 331.53 ha at an annual rate of 40.19 ha/a, mainly in the coastal waters of southeast Dongguan and northwest Shenzhen. The key issues in the key years are shown in Figure 6.

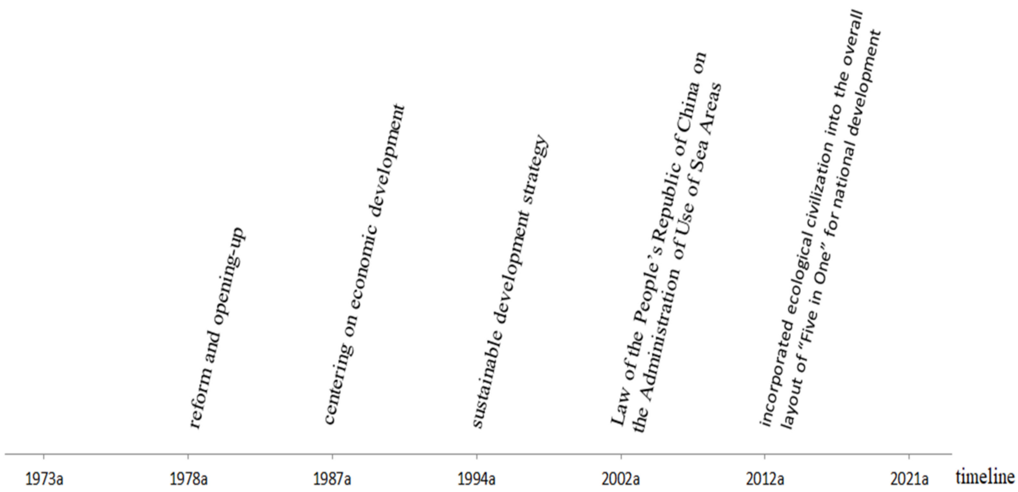

Figure 6. Key issues in the key years.

After interpreting the above-mentioned images in different periods with sea area usage authentic right data, this study divided the reclamation area into six common types according to its development and utilization: pond culture, agricultural reclamation, urban construction, transportation, industrial development, and reclaimed but unused. The area of each type and its proportion are shown in Table 5.

Table 5. Reclamation Structure in Different Periods (unit: ha).

Period	Pond Breed	Agricultural Reclamation	Urban Construction	Transportation	Industrial Reclamation	Not Used for Reclamation
1973–1978	339.99	234.58	0.00	0.00	0.00	116.05
1978–1987	2689.92	3361.24	291.49	220.82	264.21	43.01
1987–1994	1878.05	2775.37	468.17	202.89	400.26	2551.12
1994–2002	4262.36	1057.21	1008.73	699.65	133.52	171.74
2002–2012	301.59	351.23	1031.54	763.47	1261.02	1045.29
2012–2021	0.00	0.00	267.68	63.85	0.00	0.00

5. Discussion

In order to cope with sea-level rise, prevent marine disasters, and develop marine economy, many countries have carried out large-scale reclamation in the past decades [42–45]. However, the reclamation land now needs to increase the height of the embankment. Otherwise, it will cost plenty of money, people's migration, coastal use change, etc., to deal with the expected accelerated sea-level rise. In general, the total area of reclamation in the Pearl River Estuary is still increasing throughout the study period, but at a constantly lower rate. Especially in recent years, led by the concepts of building a life community of mountains, rivers, forests, fields, lakes, and grasses, and seeking the harmony between humans and the sea, the Chinese government has prioritized green and low-carbon development and held fast to the red line of marine ecological conservation, with continuous efforts to protect marine ecosystem and environment, encourage intensive and economical use of sea resources, minimize the occupation of natural space by human activities, and promote the overall green transformation in economic and social development to achieve harmonious coexistence between man and the ocean.

5.1. Analysis of the Change of Marine Space Use

In terms of the reclamation structure in different periods, during 1973–1987, the reclamation was mainly for agriculture and pond culture purposes. The combined area of the two accounted for 83.29% during 1973–1978, and 88.07% during 1978–1987. During 1987–1994, the reclamation was mainly for agriculture, remaining unused after reclaimed, and pond culture, with the combined area taking up 87.05%. The reclamation during 1994–2002 was mainly for pond culture with 58.12% of the total. From 2002 to 2012, the reclamation was largely for industrial development, urban construction, and remaining unused after reclaimed with the combined total up to 70.21%. From 2012 to 2021, urban construction was the main type, accounting for 80.74% of the total.

In terms of the changes of the utilization types, pond culture had been the main type before 2002, but then gradually declined afterwards with no new increase in recent years. The reclamation for agriculture had been the main type until 1994, but then began to decline. Urban construction took a growing proportion since 1978 and most of the reclamation projects in recent years are for this purpose; reclamation for transportation has been increasing gradually since 1994; industrial reclamation has not been the major type, and only peaked during 2002–2012; the type of being unused after reclaimed happened only for a short time, as they were converted to other uses when conditions were right. Since 2002, it is largely concentrated in the southern area of Longxue Island.

It can be seen that the land resources acquired from reclamation in the Pearl River Delta Estuary in the early stage had mainly served such primary industries as agriculture and pond aquaculture in an extensive way. With the continuous and rapid development of the marine economy and better marine resources' development and utilization, especially driven by the overall advancement of the GBA and Shenzhen as the pilot demonstration zone of socialism with Chinese characteristics, the land resources from reclamation have been gradually oriented towards the secondary and tertiary industries, including transportation, industrial development, and urban construction, which showed that the marine resources in the region are being developed in a better mode. For local governments, mastering the use of conversion characteristics of marine space at different development stages can give full play to the economic, social, and ecological benefits of the sea area.

5.2. Analysis of the Driving Mechanism of Changes in Marine Space Resources

At the forefront of China's reform and opening-up, the Pearl River Delta region is key in leading China's economic growth, playing a prominent role and holding a pivotal strategic position in the process of China's overall economic and social progress and reform and opening-up. The GBA where the Pearl River Delta is located is one of the four largest bay areas in the world, the powerhouse of China's high-quality development, and the priority area to nurture the frontrunners in this process.

The changes of the coastline in this area present a general trend of constantly moving toward the sea in either a fast or slow manner. It is one of the regions with the most drastic changes in its coastline. Before the 1970s, extensive shoal areas and tidal flats existed within the estuary, which forms the geomorphic base for the land reclamation activities [46]. The delta coastline advances, as a result of continuous riverine sediment supply and depositions. The depositional shoal morphology is shaped by convergent tidal actions within the estuary [47]. Furthermore, the sediment discharged from the upstream catchment system is blocked by islands and has continuously deposited to form abundant shallow shoal areas in the estuary. After the 1970s, coastline changes were mainly a result of man-made factors (e.g., accelerated siltation led by embankments). Human reclamation activities have never ceased in history, and increased rapidly after the 1970s (Figure 6). The scale of newly emerged land in this area is very large, and human activities such as agricultural development and urban construction are important reasons for the significant changes in the coastline of the Pearl River Estuary [48,49]. Human activities are reaching out to the coastline in greater breadth and depth, affecting the Pearl River Estuary area in the context of rapid social and economic development in recent decades [50]. Such land reclamation activities also have significant impacts on the future coastline dynamics. For example, the declined tidal prism due to the shrinking water area may accelerate natural delta coastline advance, which could be also compromised by declining riverine sediment supply, sand mining, and channel dredging in the estuary, as well as accelerated relative sea-level rise.

Sea reclamation is currently one of the major means to develop and explore the values of the coastal sea in China, which has significantly sustained China's efforts in boosting the maritime sector. Facts show that human activity is the major factor leading to the changes in the reclamation of the Pearl River Estuary. Continuous urban expansion as a result of rapid population growth further drove up the rapid extension of the land for urban construction. Take Shenzhen on the east bank of the Pearl River Estuary as an example. According to the "Shenzhen Statistical Yearbook", the number of the year-end permanent population in 1979 was 0.3141 million, and that in 2020 was 17.6338 million, and the annual average growth rate was 10.3%. In 1979, the GDP was 19.638 million yuan; the GDP in 2020 is 276,702.398 million yuan, and the annual average growth rate is 21.1%. As one of China's special economic zones, Shenzhen has a dense population distribution and rapid economic growth in the coastal zone, and reclamation has played an obvious supporting and stimulating role in population and economic growth. Shenzhen is now the most densely populated megacity on Chinese mainland and is attracting more and more new settlers prompted by the goal of a higher level of urbanization, which in turn is demanding more for the production and living space in cities. This, though, has sustained the trend for China's economic aggregate to climb at an extraordinarily fast pace; it also has occupied huge coastal land resources (e.g., cities including Guangzhou and Shenzhen have built a large number of port terminals and developed their coastal industries to capitalize on sea resources to empower their advantages in coastal transportation). As a result of less strict policies on sea resource utilization in the early days, "asking land from the sea" once was the main means for local governments to relieve their land constraints, explore space for further growth, and increase land size for industrial purposes. The changing trend of the coastline and reclamation has slowed down since the *Law of the People's Republic of China on the Administration of the Use of Sea Areas* took effect and the concept of ecological civilization was introduced, which tells well the importance of the laws, systems, and policies on marine administration.

6. Conclusions

The changes in the coastline length and reclamation size in the Pearl River Estuary are vital to the efficient use and conservation of marine resources, which not only affect the sustainable economic and social development of Guangdong Province, but also the goal of building the BGA into a "Beautiful Bay Area", an "International Bay Area", and a world-class city cluster. This paper presents the changes of the coastline and reclamation of the Pearl River Estuary after analyzing remote sensing data from 1973 to 2021 in seven sets, with 7 years as the average step length. The analysis results show that the coastline length and reclamation area in the region demonstrate an increasing trend in first a high but then low growth rate as a result of shifting national development strategies and macro-control measures in different historical periods.

In the past half century, the total coastline length of the Pearl River Estuary increased from 240.09 km to 416.00 km, up by 73.27%. The length of the natural coastline of the mainland has reduced from 136.91 km to 15.17 km, down by 88.92%, with the residual natural shoreline concentrated on the tip of the bay at the junction of Shenzhen and Hong Kong. In the same period, the total reclamation area increased by 28,256.06 ha, based on which the islands of Longxue and Hengmen on the west bank of Pearl River Estuary have gradually stretched out to the south. The southeast of Guangzhou and the eastern part of Zhongshan on the west bank of the Pearl River Estuary, and Shenzhen and Dongguan on the east bank, are advancing reclamation outward along the coast. As a part of the Pearl River Delta front, the tidal flats in this area were well developed and suitable for reclamation. The reclamation in the early days was largely for agriculture and pond culture purposes, but is shifting to transportation, industrial development, and urban construction in recent decades.

Greater demands for land resources as a result of population explosion and economic take-off have been the strong inner force driving up reclamation efforts. Due to insufficient control in the past, drastic, significant, and long-term changes have taken place in the coastline and reclaimed areas of the region. Though having boosted the blue economy to a certain extent, it lowered the quality of urban living conditions, weakened development resilience, and impaired the capacity of the ecosystem in the carbon sequestration and supply of ecological products. It has also seriously changed the regional natural geographical pattern and affected the role of the coastal region as the ecological protection barrier. The promulgation of laws, systems, and policies such as the "*Law of the People's Republic of China on the Administration of the Use of Sea Areas*" has clearly helped the conservation of coastal wetlands and further protected the space for people to be close to the sea and the living space of marine organisms.

Estuary is the hub of river basins and the sea, and the coast is the transition zone linking land and sea. The coast and estuary are thus an important zone to pool and disperse energy and material flow with various (physical, chemical, biological, and geological) processes getting coupled and varied here [51]. Located in the Economic Circle of the South China Sea, the Pearl River Estuary and the adjacent waters is one of the key marine ecological function areas in the traditional Chinese sense. It serves as the resource treasure, ecological barrier, economic artery, and strategic space of the GBA and thus is strategically positioned in China's overall development. Meanwhile, as the ocean is the largest carbon reservoir in the earth system [52], the conservation and restoration of marine ecosystems will help maintain its natural reproduction capacity, and help restore and expand ocean carbon sink. Long-term ecosystem-based coastal protection and management are critical to support sustainable coastal ecosystems in China in the future [53]. Faced with tightened resource constraints, serious environmental pollution, and degradation of the ecosystem, the future development and utilization of the Pearl River Estuary must be fit into the new era of pursuing ecological civilization by seeking coordinated management of land and ocean and coupled development of rivers and sea, and respecting the laws of nature while being equipped with such a philosophy on ecological civilization as following and protecting the nature, and prioritizing conservation and protection so as to achieve the harmonious coexistence of human and nature. China should enhance law enforcement and increase penalties and strengthen public participation in reclamation management [54]. Efforts should be made to protect the blue carbon ecosystem and avoid the over-exploitation of marine resources, fully tap the potential of the stock land resources, and improve utilization efficiency, explore resources, production capacity, and space from the ocean in a science-based and orderly way. These efforts must be made while ensuring the safety of flood discharge and tidal relief in the Pearl River Estuary, so as to contribute to carbon peak in an early date and build the region into a demonstration zone for green development.

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