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Spatiotemporal Change Patterns of Coastlines in Zhejiang Province, China, Over the Last Twenty-Five Years

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Received: 16 January 2018; Accepted: 7 February 2018; Published: 11 February 2018

Abstract: Spatiotemporal analysis of coastline land utilization is important for strengthening coastline resource management and promoting sustainable development in coastal zones. In this study, basic spatiotemporal characteristics of coastline land utilization in Zhejiang Province, China, were analyzed using remote sensing (RS) and GIS techniques. For this case, Landsat Thematic Mapper and Operational Land Imager remote-sensing image data acquired from 1990 to 2015 were collected and processed. Several indices and metrics used for quantifying and analyzing the coastline utilization in Zhejiang Province were defined and calculated through processing remote sensing data and using GIS tools. They included the intensity index of coastline change, fractal dimension of the coastline, subjectivity of coastline utilization, and the integrated coastline utilization index. The analysis results demonstrated that (1) significant coastline changes took place in Zhejiang Province, and the coastline moved seaward, while the total coastline length decreased continuously; (2) the average fractal dimension of the coastlines was 1.0922, and it was relatively stable before 2000, but declined continuously after 2000, reduced to 1.086 in 2015; (3) the artificialization index of the coastlines kept rising; (4) there were single, binary, and other multi-land use types in different coastline sections in the study area; and (5) the coastline land use intensity increased continuously from 0.25 to 0.38, and the coastline in the Xiangshan Harbour had the highest land use intensity index, reaching 0.53 in 2015, throughout the study period, and in the study area.

Keywords: coastline; Zhejiang Province; coastline changes; land utilization; coastline artificialization

1. Introduction

As one of the factors that could denote fast changes in coastal areas, the coastline has unique geographic morphology and dynamic features. It is an important sea–land boundary line [1]. Coastal countries have been shifting their economically-developing centers towards coastal regions since the 20th century. Almost 50% of global populations have been settled in regions within 100 km of coastlines [2]. Coastal zones have become regions where the most active and intensive human economic activities occur. Given the increasing demand of land by human society, large-scale sea reclamation projects have been implemented in some coastal countries and regions, resulting in coastlines moving seaward. Coastline shape is being changed at a much faster speed than that under natural conditions. This trend is opposite to that of coastal erosion caused by global sea level rise. Rapid coastline changes have a huge and negative influence on the economy, society, ecology, and environment in coastal regions. For instance, large-scale sea reclamation significantly reduced the proportion of natural coastlines in China. Overuse of coastlines, artificially straightening naturally bended coastlines, and disordered aquaculture has deteriorated ecological environment near shore areas. With the intense exploitation of marine resources, the coastal zone will become a key area for coastal economic development.

With the remote sensing (RS) and GIS techniques, many scholars have conducted many studies on monitoring coastline changes and analyzing and understanding the underlying causes of those changes. Briefly, GIS techniques can help us model and analyze spatiotemporal change patterns of coastlines, using relevant geospatial data. Nowadays, spatiotemporal analyses of coastline changes and corresponding environmental influences have become a hot research topic. Existing studies mostly focus on monitoring coastline length changes [3,4], sea and land alternation in coastal zones [5], coastline land use change, and spatiotemporal changes of fractal dimension [6,7], etc. Qualitative and quantitative analyses of coastline changes have been used to achieve these goals. For example, changes of coastline length, shape, and position can be analyzed with length value, sea–land area, fractal dimension, and change rate [8,9]. Scholars have discovered large time-span coastline change characteristics and trends, by analyzing sedimentary substances, main composition, age, and thickness of deposition on beaches, in intertidal zones, and on the continental shelf [10]. Existing coastline studies mainly focus on coastline sections with significant changes, such as those in bay and estuary areas [11,12]. Per research methods, coastline information is mainly extracted by analyses of topographic maps and multi-temporal remote sensing images in study areas [13]. The remote sensing method includes man–machine interaction and visual interpretation [14], multispectral classification [15], image segmentation [16], etc. For example, employing Landsat Multispectral Scanner, Thematic Mapper (TM), and Operational Land Imager (OLI) images as a major data sources, coastlines were extracted by using a normalized difference water index segmented by a threshold of zero [17,18]. Influencing factors of coastline changes can be divided into three types: global environmental processing [19], coastal zone environmental processing [20], and human impacts [21]. Direct coastline changes caused by human activities are strongly destructive and irreversible. The degradation of environmental functions is difficult to recover from, and has a high cost. In general, the influencing factors may be analyzed in three ways: (1) the analysis based on influencing factors and influencing mechanism of actual coastal changes, which means that effects of environmental factors and evolution on coastline changes are analyzed by comparing coastal location changes before and after events and in different regions [22]; (2) the mathematical analysis method, based on the correlation analysis of environmental changes with coastline changes, which is determined by mathematically analyzing influencing factors, or by correlation, analyzing the changes of influencing factors with coastline changes [23]; and (3) modeling analysis and simulation based on coastline changes and their influencing factors, where the influences of natural processes or factors on coastline changes are analyzed based on modeling of coastline changes in considering the natural processes and factors [24].

It is widely accepted that position, developing trends, and morphological changes of coastlines are caused by both natural environmental evolution and human activities [25] in coastal zones. The changes not only reflect coastal environmental features and evolutionary trends, but also show the relationships among socio-economic development, ecological environmental changes, and policies regarding coastal zones. Therefore, studies on spatiotemporal changes of coastline land utilization [26] and spatial distribution patterns of the land use types in a certain coastal zone are one of the fundamental tasks for coastal environmental monitoring, resource exploitation, and coastal management [27]. The knowledge derived from the studies is invaluable to optimizing the spatial patterns of coastlines, coastal resource management, and sustainable development. Therefore, in this study, we propose to investigate spatiotemporal change patterns of coastlines in the study area. For this case, position, and type information (considering only mainland coastlines in this study) of coastlines in Zhejiang Province from 1990 to 2015 was extracted by applying RS and GIS techniques to spatiotemporal analysis of characteristics of coastline changes driven by anthropogenic impacts. Moreover, spatial evolutions of coastline land utilization in different coastal zones were disclosed in this study. In the paper, after this introductory section, the research data and methodology are provided in the next section. Relevant results derived from this study and relatively detailed analyses to those results are given in Section 3. In Section 4, thoughts and implications associated with the research results are discussed, and finally, in the last section, several conclusions derived from this study are summarized.

2. Data and Methods

2.1. Study Area

Zhejiang Province is located in the southeast coastal region in China, south of the Yangtze River Delta. It possesses a good geographical location and long zigzag coastline. The mainland coastline starts from Jinsha Bay in Pinghu County in the north, and extends to Hutoubi in the Cangnan County in the south, covering a total length of 1805 km. It is about 10% of the total mainland coastline in China. Coastal environments in Zhejiang are complicated and unstable, and different sections possess their own unique characteristics. There are numerous islands in the extensive sea area, including 3061 islands, each with an area over 500 m^2 [28]. Coastal zones in Zhejiang Province have excellent natural conditions, rich marine resources, developed economies, and dense cities. Sea reclamation in Zhejiang Province has been implemented for over 1000 years. Particularly, lots of sea reclamation projects were conducted during the last 60 years because of urban and rural economic development, resulting in rapid land use changes in the coastal zones. Despite meeting the demand for land, sea reclamation has brought about considerable ecological environmental problems, such as reduction of coastal wetlands, partial changes of hydrological and hydrodynamic conditions, interference in normal service of channels, damages to fishery resources, etc. Coastline resources have become an important constraint against sustainable socioeconomic development in coastal zones in Zhejiang Province.

Of the 11 cities in the coastal zones, seven are prefecture-level cities, which belong to the secondary administrative region between province and county levels in Zhejiang Province, including Jiaxing, Hangzhou, Shaoxing, Ningbo, Taizhou, Wenzhou, and Zhoushan. However, some prefecture-level cities (e.g., Hangzhou and Shaoxing) have a very short coastline and only a single coastline type. To analyze spatial distribution patterns of coastline, the study area was divided into seven natural coastal zones according to spatial geographical differences (Figure 1).

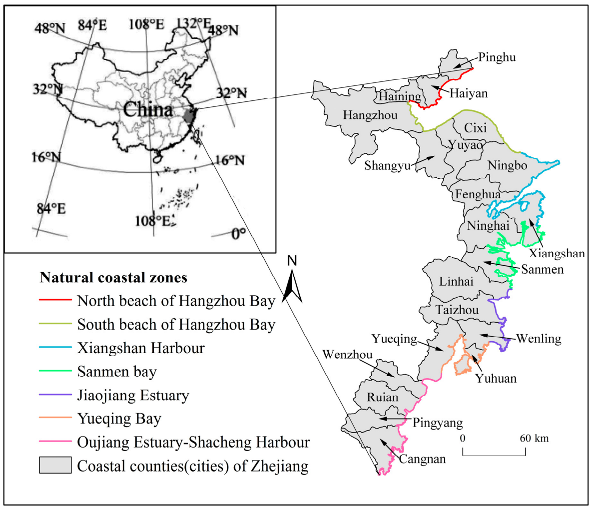


Figure 1. The location map of the study area.

2.2. Data Sets and Processing

In this study, six scenes of Landsat TM and OLI remote sensing images (acquired in years 1990, 1995, 2000, 2005, 2010 and 2015), administrative maps of prefecture-level cities in Zhejiang Province, and 1:250,000 topographic map of Zhejiang Province were used as the basic data sources. Remote sensing images were first preprocessed by using software ENVI5.2 [29], including geometric rectification, image registration, and image mosaicking. Based on coastal geographical characteristics, field survey results in Zhejiang Province, the 1:250,000 map of Zhejiang Province, and Google Earth images, the mainland coastline in Zhejiang Province was divided into two categories: natural coastlines (including bedrock coastline, gravel coastline, sludge coastline, and estuary coastline) and artificial coastlines (including aquatic cultivation coastline, harbor coastline, urban and industrial coastline, as well as protective coastline). Interpretation keys for each coastline type were determined [30].

After reflectance, spectral characteristics of the land cover types in coastline zones were determined, and a single-band edge test on remote-sensing images was carried out to enhance sea-land boundary lines [11]. Next, the accurate position of the transient flowage line (level) was extracted by using linear construction functions in ArcGIS (ESRI ArcGIS Desktop 10.2) through a visual interpretation. The horizontal distance between the flowage line and high-water line was calculated according to the sea level at a tide station, average high-water level, and beach gradient in the study area. Different thresholds of the horizontal distance were set, using ArcGIS tools to eliminate errors and determine real positions and types of coastlines [31]. Finally, the lengths of different types of coastlines in different years were calculated automatically by using the GIS-based vector data length calculation tool (ArcGIS).

2.3. Intensity of Coastline Change

The intensity of coastal change was expressed by an annual change rate (%) of coastline length in different coastal zones [3]. The rate was a criterion to compare spatiotemporal change of unit coastline length between different sections. The calculation formula is:

$$ICLI_{ij}(\%) = \frac{L_j - L_i}{L_i(j-i)} \times 100 \tag{1}$$

where $ICLI_{ij}$ is the intensity of coastline length change in a unit section from year i to year j ($j > i$); L_i and L_j are the coastline lengths in year i and year j, respectively. If $ICLI_{ij}$ is negative, the coastline shortens; otherwise, the coastline increases. The higher the $|ICLI_{ij}|$, the stronger the intensity of coastline change.

2.4. Fractal Dimension of Coastline

A fractal dimension reflects the curvature and complexity of a coastline. Gauge method (divider method) [32], network method (box-counting method) [33] and random noise method [34] are often used to calculate the fractal dimension of a coastline. Although both the gauge method and the grid method can be used to calculate the fractal dimension of a shoreline, the gauge method is a traditional manual method, and cannot be fully automatically carried out at present. However, the grid method is common and easy to carry out by computer software, such as Matlab and ArcGIS, which can limit errors caused by a manual method. Therefore, fractal dimensions of a mainland coastline in Zhejiang Province in different years were calculated based on a grid method [35]. Firstly, coastline vector data were converted into raster data by the ArcTool box module in ArcGIS for binarization processing. Grids that cover coastlines in the study area were generated. Statistics on the grid quantity (N) corresponding to coastline length (ε) in different years were implemented. Finally, linear regressions on ln$N$ and lnε were conducted to obtain fractal dimension values of coastlines. A high fractal dimension indicates high curvature and complexity of a coastline. The change rate of fractal dimension can also reflect changes of artificial reforming intensity or the coastal erosion/sedimentation state [36].

According to the standards of State Bureau of Quality Technical Supervision in China, the principal scale map was digitalized by referring to the conversion formula [7] and common scale of the Zhejiang Map, to get grid length ε. To protect unique increment between length values of network structures, two values (1000 m and 2500 m) were added, and a length series for calculation of fractal dimensions was constructed (Table 1).

Table 1. Sizes of grid cells.

Grid Length, ε (m)	Scale Denominator, Q
75	250,000
150	500,000
300	1,000,000
600	2,000,000
900	3,000,000
1000	Not available
1100	3,500,000
1200	4,000,000
1500	5,000,000
1800	6,000,000
2500	Not available
3000	10,000,000

2.5. Subjectivity of Coastline Utilization

The subjectivity of coastline utilization can indicate the structure and significance of subjective coastlines within a specific region. For this study, it was calculated by the method of landscape dominance determination in landscape ecology [37], and was corrected according to experts' suggestions, actual demands, and the situation of the coastline in Zhejiang Province. Finally, the coastline utilization direction and subjectivity model for a quantitative assessment of spatial coastline pattern was presented, as seen in Table 2. The subjectivity of coastline utilization is a proportion of subjective coastlines within a specific region.

Table 2. The subjective indices of coastline development and utilization.

Subjectivity of Coastline Utilization	Requirement
Single principal	A certain type $l_i > 0.45$
Binary, ternary principal	Each type $l_i < 0.45$, but two or more types $l_i > 0.2$
Multivariant principal	Each type $l_i < 0.45$, but only one $l_i > 0.2$
Non principal	Each type $l_i < 0.2$

Note: l_i represents a ratio of the length of shoreline of type i to the length of total shoreline in a given region.

2.6. Integrated Coastline Utilization Index

In this study, an integrated coastline utilization index was used as a quantitative criterion to measure influences of human activities on coastal resources and environment. Firstly, impacts of a coastline type on resources and environment in a natural coastal zone were expressed by the resource and environmental impact factor (P). The primary index system was established by integrating natural and ecological influencing factors. Next, selected indices were assessed and further selected by 20 experts in different fields (including geography, oceanography, and environmental science). In this way, a final evaluation index system was established. The judgment matrix of the evaluation index system was set up according to hierarchical analysis and experts' opinion. Then, weight coefficients of different indices were determined. Finally, evaluation weights of P for different coastline types were calculated (Table 3).

Table 3. Resource and environment impact factors for different types of coastlines.

Coastline Type	Natural Coastline	Urban and Industrial Coastline	Protective Coastline	Harbour Coastline	Hquatic Cultivation Coastline
Factor	0.1	1	0.2	0.8	0.6

Accordingly, the integrated coastline utilization index (ICUI) may be calculated as follows [26]:

$$ICUI = \frac{\sum_{i=1}^{n} li \times Pi}{L} \tag{2}$$

where $ICUI$ is the integrated coastline utilization index, n is the number of coastline types, l_i is the length of coastline type i, P_i is the resource environment impact factor of coastline type i ($0 < P_i \leq 1$), and L is the total mainland coastline length.

3. Results and Analysis

3.1. Coastline Changes and Their Intensity

Spatial changes of the mainland coastline in Zhejiang Province during the last 25 years were delineated from remote sensing image interpretation and coastline vectorization analysis results (Figure 2). Coastline lengths (Table 4) and change rates (Figure 3) of different coastline sections in the study area were calculated.

Table 4. A summary of coastline changes from 1990 to 2015.

	Length (km)					
	1990	1995	2000	2005	2010	2015
North Beach of Hangzhou Bay	104.48	103.33	105.31	111.83	100.06	99.96
South Beach of Hangzhou Bay	166.12	167.48	156.91	174.54	165.62	159.89
XiangshanHarbour	414.88	412.57	390.71	392.33	369.11	374.58
SanmenBay	491.81	481.28	474.87	451.93	458.71	460.41
Jiaojiang Estuary	180.40	172.98	192.83	170.00	185.84	186.53
Yueqing Bay	275.55	304.43	286.74	259.54	226.42	236.04
Oujiang Estuary-Shacheng Harbour	271.22	271.40	267.87	265.73	281.99	287.71
Total	1904.45	1913.45	1875.24	1825.89	1787.74	1805.11

Results from Figure 2 demonstrate that the mainland coastlines in Zhejiang Province moved toward sea areas continuously during the study time period. Total mainland coastline length in the study area shrank in a fluctuating pattern. It was reduced by 99.34 km during the last 25 years, with an annual average shrinkage rate of 3.97 km. The total coastline length was 1904.45 km in 1990, which was increased to 1913.45 km in 1995, and then decreased continuously. The total coastline length was decreased to 1787.74 km in 2010, and then increased to 1805.11 km in 2015. An intensive development of artificial coastlines occurring between 2000 and 2005 might have resulted in the highest intensity of coastline changes. The average change rate of coastline shrinkage was 9.87 km/y. One major driver to result in this rate is increasing human activities during this period. Continuous straightening and construction of artificial structure decreased the curvature of a coastline, and thus shortened the total coastline length. However, new artificial coastlines were also formed continuously by the reclamation of sea areas and tidelands. Coastlines intruded toward the sea area continuously, which might lengthen the total coastline.

By referring to Table 4, lengths of coastline sections in the study area from 1990 to 2015 had the following order, from longest to shortest: Sanmen bay, Xiangshan Harbour, Yueqing Bay, Oujiang Estuary-Shacheng Harbour, South Beach of Hangzhou Bay and Jiaojiang Estuary, and North Beach of Hangzhou Bay. During the study period, the total coastline lengths of North Beach of Hangzhou Bay, Jiaojiang Estuary, and Oujiang Estuary-Shacheng Harbour increased slightly, whereas those of the rest of coastline sections showed decreasing patterns. Coastline length in the Xiangshan Harbour suffered from the maximum shrinkage (40.30 km), followed by Yueqing Bay. The coastline in North Beach of Hangzhou Bay experienced the minimum shrinkage, only 4.52 km. Figure 3 indicates the changes of lengths of the seven coastline sections in the different time periods at seven directions. The farther the corresponding points in each coastline section are from the center, the greater the length of the coastline section in the study area increases. Otherwise, the more the length of the total coastline section reduces.

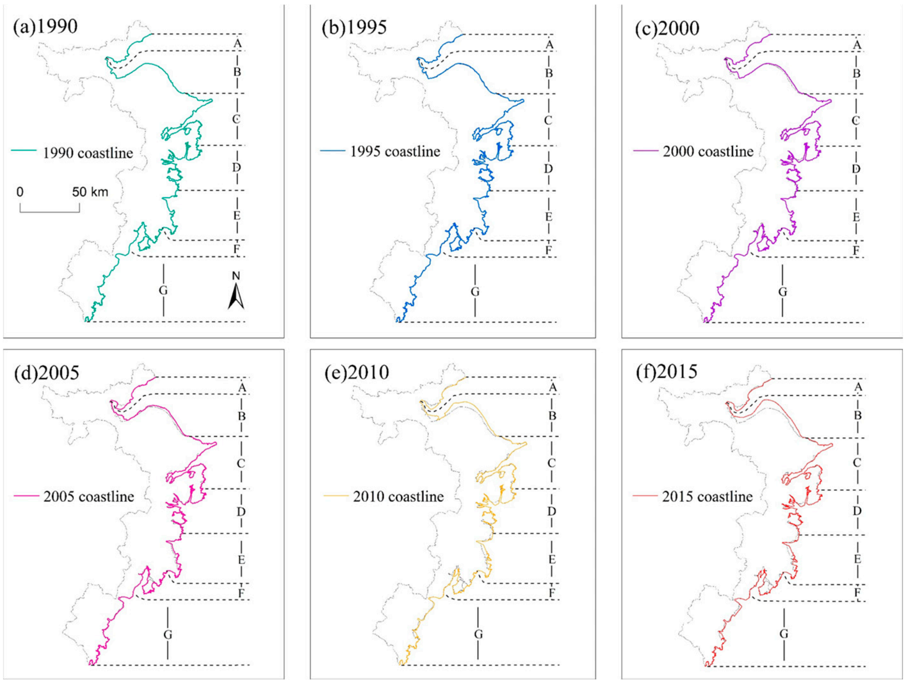


Figure 2. A map of coastline changes in Zhejiang Province from 1990 to 2015. A: North beach of Hangzhou Bay; B: South beach of Hangzhou Bay; C: Xiangshan Harbour; D: Sanmen bay; E: Jiaojiang Estuary; F: Yueqing Bay; and G:Oujiang Estuary-Shacheng Harbour. (**a**): Coastline pattern in 1990; (**b**): Coastline pattern in 1995; (**c**): Coastline pattern in 2000; (**d**): Coastline pattern in 2005; (**e**): Coastline pattern in 2010; (**f**): Coastline pattern in 2015.

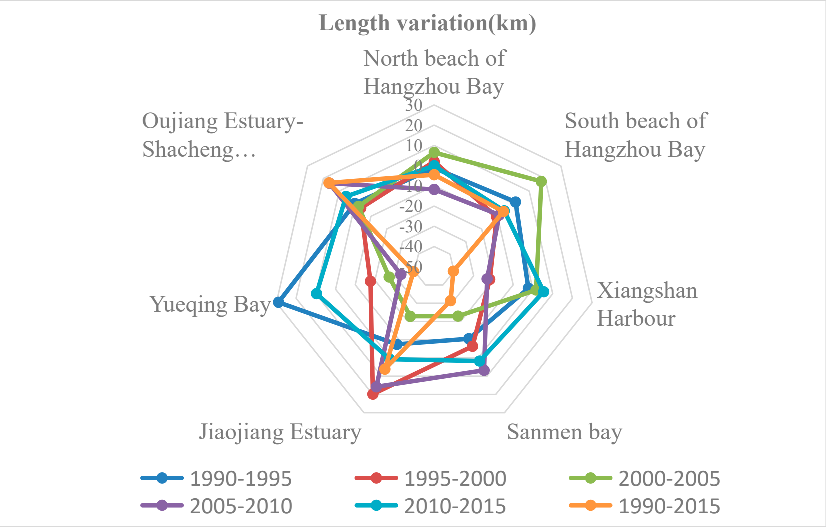
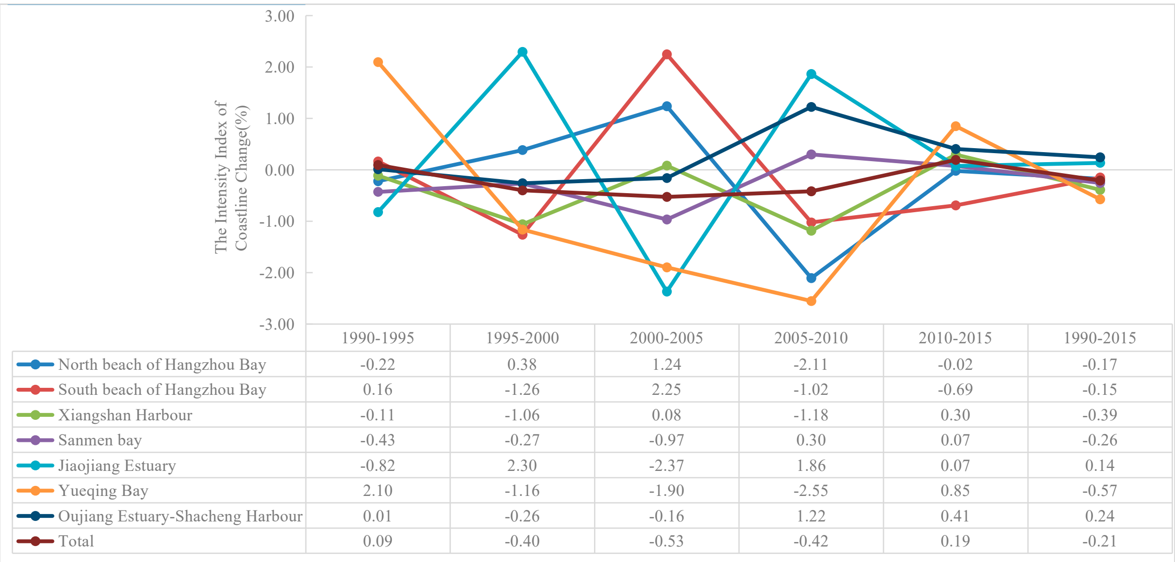


Figure 3. A presentation of coastline changes in the seven coastline sections from 1990 to 2015.

Intensities of coastline changes in different sections were compared, according to results calculated with Equation (1) (Figure 4). The intensity of overall coastline changes in Zhejiang Province was −0.21% from 1990 to 2015. The intensity of coastline changes was relatively low during 1990 to 1995, but kept at a high level later, reaching −0.4%, −0.53%, and −0.42% in the following three years, respectively. The rate decreased in the last five years, and reached only −0.19%. The coastline changes in Yueqing Bay and Xiangshan Harbor fluctuated violently during the last 25 years. The average intensities of coastline changes in those two coastline sections were −0.57% and −0.39%, respectively. The highest change rate occurred from 2005 to 2010 in both sections (−2.55% and −1.18%, respectively). Intensity of coastline changes in Jiaojiang Estuary was the lowest (only 0.14%).



	1990-1995	1995-2000	2000-2005	2005-2010	2010-2015	1990-2015
North beach of Hangzhou Bay	-0.22	0.38	1.24	-2.11	-0.02	-0.17
South beach of Hangzhou Bay	0.16	-1.26	2.25	-1.02	-0.69	-0.15
Xiangshan Harbour	-0.11	-1.06	0.08	-1.18	0.30	-0.39
Sanmen bay	-0.43	-0.27	-0.97	0.30	0.07	-0.26
Jiaojiang Estuary	-0.82	2.30	-2.37	1.86	0.07	0.14
Yueqing Bay	2.10	-1.16	-1.90	-2.55	0.85	-0.57
Oujiang Estuary-Shacheng Harbour	0.01	-0.26	-0.16	1.22	0.41	0.24
Total	0.09	-0.40	-0.53	-0.42	0.19	-0.21

Figure 4. The coastline change rates in coastline sections in Zhejiang Province from 1990 to 2015.

3.2. Fractal Dimension of the Coastline

The length of a coastline is a more accurate variable, but it is not a good measure of describing the spatial characteristics of the coastline. However, the fractal dimension variable is an objective measure of describing the coastline, and is a comprehensive mathematical expression of coastline spatial form [6]. In each time period, the fractal properties of shorelines exist objectively, and the fractal dimension is a good parameter to characterize its self-similar characteristics. It reflects the curvature and complexity of a coastline. A higher fractal dimension indicates a higher curvature and complexity of a coastline. The change rate of a fractal dimension can also reflect changes of artificial reforming intensity or the coastal erosion/sedimentation state.

The statistics on a grid quantity (N) and coastline length (ε) are listed in Table 5. Regression analysis on $\ln N$ and $\ln \varepsilon$ was carried out (Figure 5). The fractal dimensions of mainland coastlines in Zhejiang Province from 1990 to 2015 were calculated (Figure 6) to describe the curvature and complexity of the coastlines. The tectonics in Zhejiang Province belong to the Huaxia fold belt with a fracture development. There are tremendous mountains and hills, bedrock coastlines, and bays in the province. Coastlines follow a zigzag shape with complex structures. Under the integrative effect of natural forces and human activities, an average fractal dimension of the mainland coastline in Zhejiang Province during the last 25 years was only 1.0922, which was slightly lower than that of the mainland coastline in China, calculated by Ma et al. [6] The fractal dimension of the coastline in Zhejiang Province was relatively stable before 2000, but declined continuously after 2000. This might be caused by the intensive artificial coastline utilization and the process of urbanization, including the reconstruction of natural coastlines into artificial coastlines and continuous changes of coastline shape and composition. Fractal dimension of the coastline decreased to 1.086 in 2015, reflecting a direct, high-intensity exploitation of the coastlines.

There is a long mainland coastline in Zhejiang Province, which presents significant spatial morphological characteristics, due to natural factors and regional differences in artificial development way and intensity. The fractal dimension of a coastline in geographical units was further calculated (Figure 7). The fractal dimensions of the coastlines in North Beach and South Beach in Hangzhou Bay and Xiangshan Harbor were smaller than the average fractal dimension throughout the whole study period. Due to effects of mud sedimentation and sea reclamation, the fractal dimension of the coastline in a large-scale intertidal zone in South Beach of Hangzhou Bay changed significantly, and decreased to a valley in 2015. Sanmen Bay is surrounded by mountains in the east, north, and west, which forms a high curvature of coastline and complicated terrain. The fractal dimension was always the highest (>1.14) in Zhejiang Province, and its coastal curvature and complexity were also stable during the study period. However, fractal dimensions of Jiaojiang Estuary, Yueqing Bay, and Oujiang Estuary-Shacheng Harbour fluctuated gently and were slightly higher than the average value. According to the varying range and spatial distribution of the fractal dimension values of the coastlines, the mainland coastline in Zhejiang Province might be divided into three major sections: a low-value section (Hangzhou Bay-Xiangshan Harbour), medium-value section (Jiaojiang Estuary-Shacheng Harbour), and high-value section (Sanmen Bay).

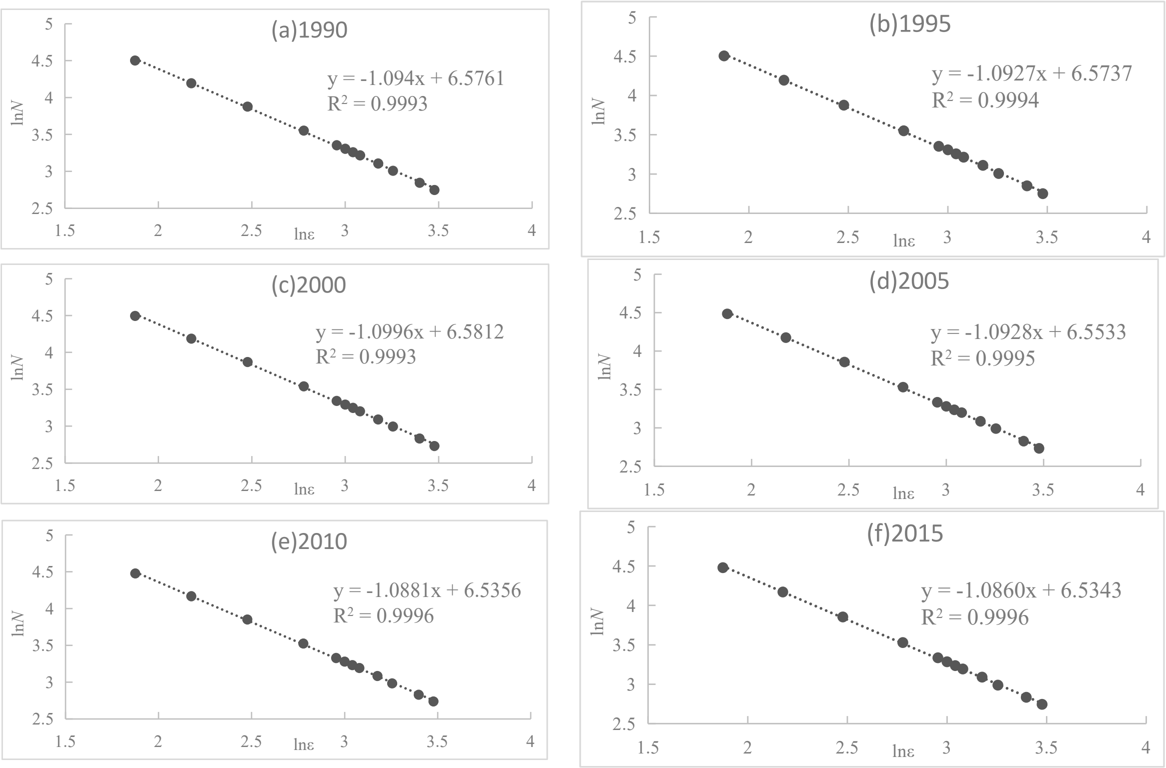


Figure 5. ln$N$–lnε linear regression equations for different years. (**a**): 1990 ln$N$–lnε linear regression; (**b**): 1995 ln$N$–lnε linear regression; (**c**): 2000 ln$N$–lnε linear regression; (**d**) 2005 ln$N$–lnε linear regression; (**e**): 2010 ln$N$–lnε linear regression; (**f**): 2015 ln$N$–lnε linear regression.

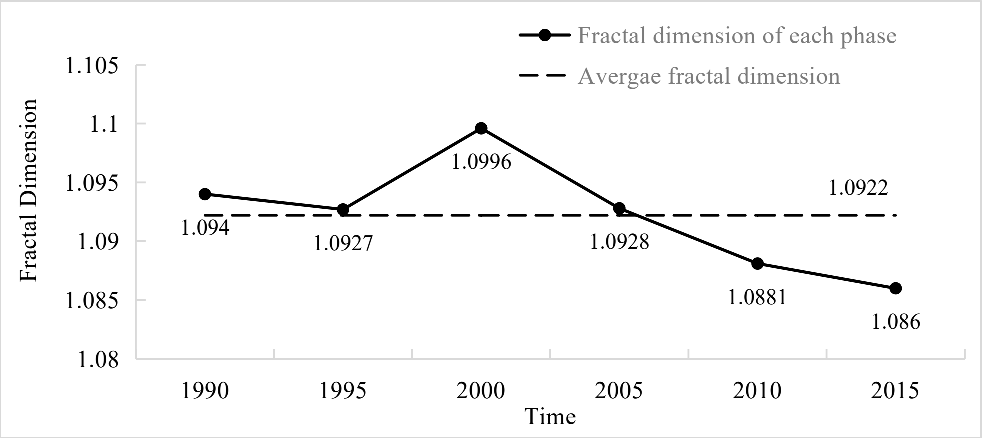


Figure 6. The coastline fractal dimension in Zhejiang Province, 1990–2015.

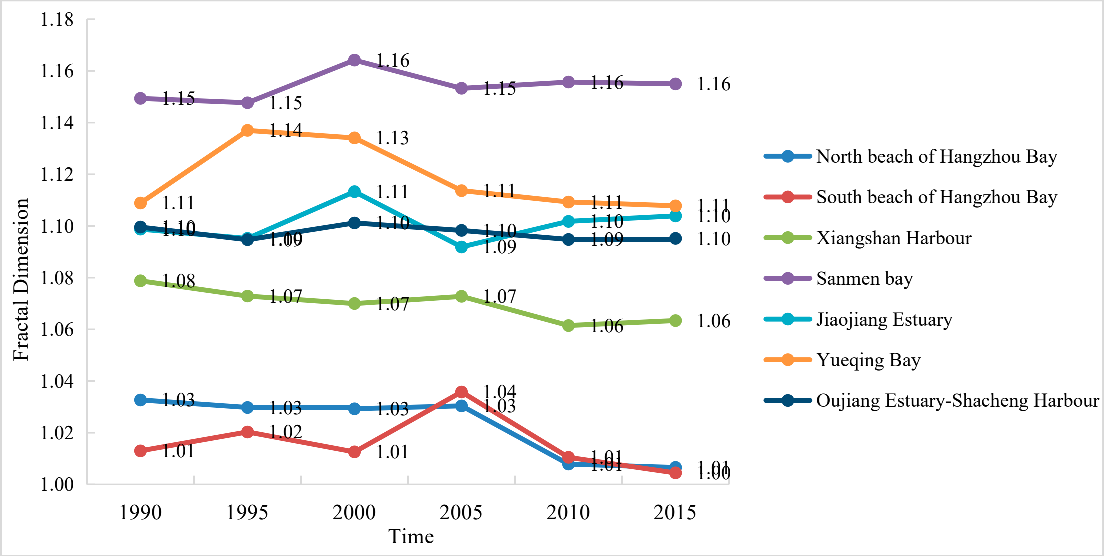


Figure 7. The spatiotemporal changes in fractal features of the coastlines from 1990 to 2015.

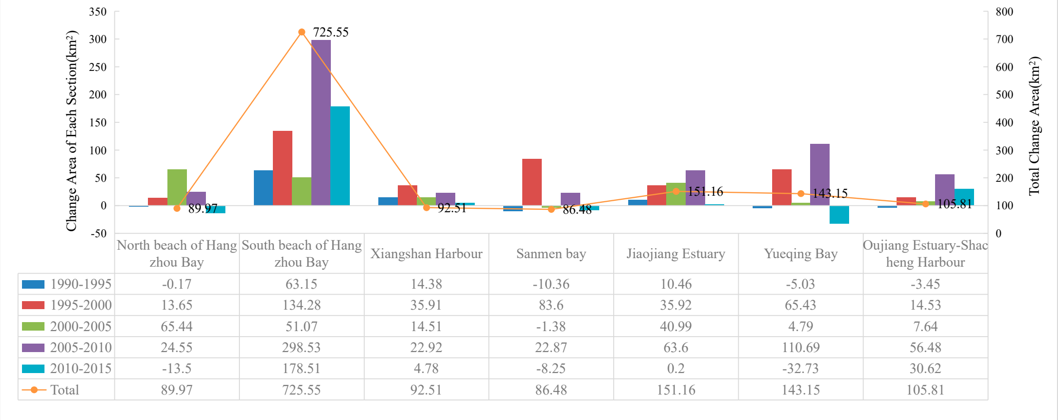
Table 5. Different years of measurement edge length (ε) corresponding to the number of grids (N).

Scale Denominator, Q	**Grid Length, ε (m)**	**The Number of Grids for Cover Coastlines, $N(\varepsilon)$**					
		1990	**1995**	**2000**	**2005**	**2010**	**2015**
250,000	75	31,767	31,895	31,290	30,509	29,974	30,180
500,000	150	15,624	15,674	15,389	14,941	14,713	14,823
1,000,000	300	7542	7530	7423	7207	7106	7155
2,000,000	600	3568	3552	3474	3394	3344	3376
3,000,000	900	2258	2256	2201	2154	2128	2162
Not available	1000	2022	2037	1962	1907	1899	1927
3,500,000	1100	1814	1810	1771	1722	1704	1725
4,000,000	1200	1647	1639	1592	1583	1554	1561
5,000,000	1500	1278	1290	1234	1217	1213	1229
6,000,000	1800	1018	1017	989	979	961	973
Not available	2500	699	708	681	673	673	682
10,000,000	3000	559	563	539	542	547	555

3.3. Sea–Land Pattern Changes

Coastal changes indicate the changes of not only the length and curvature, but also the land areas in the coastal zones. Since a coastline is an open line, the coastal zone refers to a region enclosed by the coastline and fixed internal boundary. Coastal towns and villages were used to determine the internal boundary, and coastlines were used as the external boundary of coastal zones. The changes of coastal zones caused by coastline changes can be estimated by calculating the polygonal area changes in different time periods (Figure 8).

Between 1990 and 2015, the mudflat area in Zhejiang Province was expanded by 1394.64 km^2, showing a growth rate of 55.79 km^2/y. The highest growth rate was achieved from 2005 to 2010, reaching 119.93 km^2/y. The change rates in different sections varied. The largest change took place in the South Beach in Hangzhou Bay. The coastline moved toward the Hangzhou Bay by 29.02 km^2/y. The Hangzhou Bay is in the estuary of Qiantang River and Caoe River, and its sedimentation has formed a vast intertidal zone, which is very suitable for reclamation. The growth rate of the mudflat in Sanmen Bay was only 3.46 km^2/y—the smallest among those of all sections. In the rest of coastline sections, coastlines intruded toward the sea, and the mudflat area was increased during the study period.



	North beach of Hang zhou Bay	South beach of Hang zhou Bay	Xiangshan Harbour	Sanmen bay	Jiaojiang Estuary	Yueqing Bay	Oujiang Estuary-Shac heng Harbour
1990-1995	-0.17	63.15	14.38	-10.36	10.46	-5.03	-3.45
1995-2000	13.65	134.28	35.91	83.6	35.92	65.43	14.53
2000-2005	65.44	51.07	14.51	-1.38	40.99	4.79	7.64
2005-2010	24.55	298.53	22.92	22.87	63.6	110.69	56.48
2010-2015	-13.5	178.51	4.78	-8.25	0.2	-32.73	30.62
Total	89.97	725.55	92.51	86.48	151.16	143.15	105.81

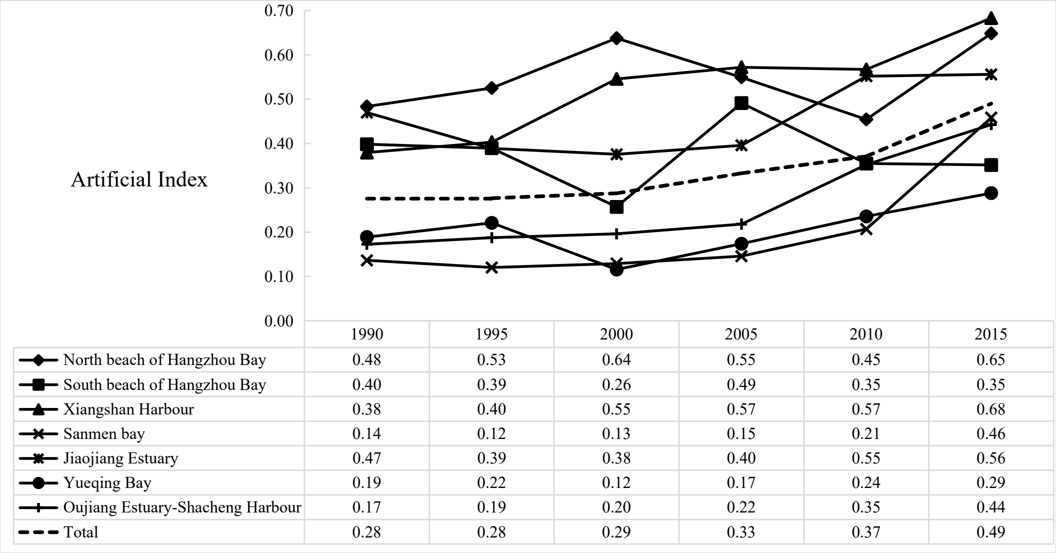
Figure 8. The changes of the mudflat area in Zhejiang Province from 1990 to 2015.

3.4. Coastline Artificialization Index Analysis

Coastline artificialization refers to the process in which natural coastlines are converted into artificial coastlines by human activities. The coastline artificialization index is used to represent the intensity of coastline artificialization in a region. It is equal to the proportion of artificial coastline length to the total coastline length in the region. With the increasing length of an artificial shoreline, that of the natural shoreline will inevitably decrease, which may lead to a series of environmental problems, such as shoreline erosion and habitat loss for aquatic animals. Therefore, it is greatly significant to study the temporal and spatial variation of the artificial shoreline ratio for coastal management, and to solve coastal environmental problems. A higher coastline artificialization index represents larger impacts of human activities on coastlines and more serious damage to natural coastlines.

The changes of the coastline artificialization index in the study area were calculated (Figure 9). The coastline artificialization index in Zhejiang Province increased continuously from 0.28 in 1990 to 0.49 in 2015. Jiaojiang Estuary and Oujiang Estuary-Chacheng Harbour, which mainly have bedrock coastlines, have suffered serious tidal erosion. Both were developed into harbors because of their deep water, thus increasing the artificialization index. The coastline artificialization indexes of South Beach in Hangzhou Bay, Sanmen Bay, and Yueqing Bay fluctuated due to effects of natural sedimentation and sea reclamation. Among the natural coastal zones, the North Beach in Hangzhou Bay, Xiangshan Harbor, and Jiaojiang Estuary had higher coastline artificialization indices (>0.45). The North Beach in Hangzhou Bay was mainly reclaimed as aquaculture land, farmland, and damp sand. Xiangshan

Harbor was mainly developed as a port. Artificial coastlines in the South Beach in Hangzhou Bay and JiaojiangEstuary-Chacheng Harbour counted for 20–40% of the total coastline area. Natural coastal zones in Sanmen Bay and Yueqing Bay were well protected, showing the lowest artificial artificialization index (only 0.20).



	1990	1995	2000	2005	2010	2015
◆ North beach of Hangzhou Bay	0.48	0.53	0.64	0.55	0.45	0.65
■ South beach of Hangzhou Bay	0.40	0.39	0.26	0.49	0.35	0.35
▲ Xiangshan Harbour	0.38	0.40	0.55	0.57	0.57	0.68
× Sanmen bay	0.14	0.12	0.13	0.15	0.21	0.46
✱ Jiaojiang Estuary	0.47	0.39	0.38	0.40	0.55	0.56
● Yueqing Bay	0.19	0.22	0.12	0.17	0.24	0.29
+ Oujiang Estuary-Shacheng Harbour	0.17	0.19	0.20	0.22	0.35	0.44
- - - Total	0.28	0.28	0.29	0.33	0.37	0.49

Figure 9. The artificial index of each coastline section in Zhejiang Province from 1990 to 2015.

3.5. Evaluation of Subjectivity of Coastline Utilization

The subjectivity of coastline utilization can indicate the structure and the significance of subjective coastlines within a specific region. The temporal variation of the subjectivity degree of a shoreline can describe the change of the type and structure of the main shoreline in a region macroscopically, and can reflect the method and intensity of human activities in the region. Principal types and subjectivity changes of coastline utilization in Zhejiang Province during the last 25 years were compared and analyzed, based on data derived from years 1990, 2000, 2010 and 2015 remote sensing images (Table 6).

There was a single principal coastline utilization type in the South Beach in Hangzhou Bay, Sanmen Bay, and Oujiang Estuary-Shacheng Harbor. The subjectivities of coastline utilization in the South Beach of Hangzhou Bay and Sanmen Bay fluctuated, and both sections have heavy sedimentation and predominantly sludge coastlines. Extensive intertidal resources in the South Beach in Hangzhou Bay built a good foundation for large-scale sea reclamation projects. The Sanmen Bay, which possesses rich intertidal resources and good ecological environmental protection, became an important aquaculture and ecological base. Continuous sea and bay reclamation for agricultural use were observed. The Oujiang Estuary-Shacheng Harbor lies at the foot of Yandang Mountain and mainly has bedrock coastlines. Its subjectivity declined continuously with the intensive human activities.

The Xiangshan Harbour is a narrow, semi-enclosed bay, which has a low water exchange capacity and vulnerable marine ecosystem. Fish farming is a major marine development activity. Xiangshan Harbour is an important ecological preservation area in Zhejiang Province, and maintains a binary subjective coastline structure composed of bedrock coastline and aquatic coastline. However, its subjectivity changed over time.

The coastline utilization structure in the Jiaojiang Estuary evolved from a binary structure to a ternary structure, and then back to a binary structure again. Fish farming is a major marine development activity, and presents an extensive trend. The principal and secondary coastline types were aquatic coastline and bedrock coastline in 1990. Subsequently, sludge coastline became the secondary type, with a continuous accumulation of mud. In 2015, bedrock coastline and aquatic coastline became the principal and secondary types again.

Table 6. The principal types of coastlines in Zhejiang Province from 1990 to 2015.

	1990			**2000**			**2010**			**2015**		
	Shoreline Structure	**Principal Types**	**Subjectivity**	**Shoreline Structure**	**Principal Types**	**Subjectivity**	**Shoreline Structure**	**Principal Types**	**Subjectivity**	**Shoreline Structure**	**Principal Types**	**Subjectivity**
North beach of Hangzhou Bay	ternary	aquatic cultivation sludge bedrock	0.38 0.25 0.24	binary	aquatic cultivation sludge	0.43 0.23	single	sludge	0.48	ternary	urban and industrial sludge aquatic cultivation	0.33 0.28 0.22
South beach of Hangzhou Bay	single	sludge	0.57	single	sludge	0.72	single	sludge	0.63	single	sludge	0.62
Xiangshan Harbour	binary	bedrock aquatic cultivation	0.42 0.3	binary	aquatic cultivation bedrock	0.29 0.26	binary	bedrock aquatic cultivation	0.24 0.23	binary	bedrock aquatic cultivation	0.29 0.22
Sanmen bay	single	sludge	0.51	single	sludge	0.57	single	sludge	0.53	single	sludge	0.5
Jiaojiang Estuary	binary	aquatic cultivation bedrock	0.41 0.36	ternary	bedrock sludge aquatic cultivation	0.35 0.27 0.21	binary	bedrock aquatic cultivation	0.39 0.28	binary	bedrock aquatic cultivation	0.39 0.27
Yueqing Bay	binary	bedrock sludge	0.41 0.4	single	sludge	0.54	binary	sludge bedrock	0.41 0.35	binary	sludge bedrock	0.37 0.34
Oujiang Estuary-Shacheng Harbour	single	bedrock	0.56	single	bedrock	0.51	single	bedrock	0.47	single	bedrock	0.46

The coastline utilization structure in North Beach in Hangzhou Bay evolved from the ternary structure to a single structure, and then back to the ternary structure again. In 1990, aquatic coastline occupied the position of principal coastline, and the subjectivity was 0.38. Sludge coastline and bedrock coastline were identified as the secondary and third types. Later, mud was deposited again along the outside of the artificial coastline, and a sludge beach was developed. Consequently, the sludge coastline became a single subjective type. Subsequently, urban and industrial coastlines occupied the dominant role with the intensive sea reclamation activities. The subjectivity was 0.33.

The coastline utilization structure in Yueqing Bay evolved from the binary structure to single structure, and then back to the binary structure. With the rich fishery resources in the section, fish farming was mainly supported by mudflat aquaculture and sea reclamation aquaculture. Bedrock coastline and sludge coastline were the major coastline utilization types in 1990. The sludge coastline became the unique coastline type in 2000, and the subjectivity reached to 0.54. Later, a binary coastline utilization structure composed of sludge coastline and bedrock coastline was formed with the growth of the proportion of artificial coastline in the section.

4. Discussion

As a "third force", human activities in coastal zones in Zhejiang Province, including rapid economic development, sea reclamation, and harbour construction, become an important way to produce sea food and expand living spaces. However, these activities have brought about profound impacts on the mainland coastline. Unreasonable exploitations of coastal intertidal resources and nearshore resources not only changed the basic condition and spatial pattern of mainland coastline in Zhejiang Province, but also caused various ecological issues (e.g., resource shortage and environmental deterioration) in coastal zones. Therefore, it is necessary to define and analyze the integrated coastline utilization index in Zhejiang Province, in order to solve existing problems, provide scientific guidance on coastal utilization and protection, and ensure sustainable economic development in coastal zones.

The integrated coastline utilization index in Zhejiang Province for different coastal zones was discussed based on Equation (2). It could be clearly seen from Figure 10 that the integrated coastline utilization index in Zhejiang Province increased from 0.25 in 1990 to 0.38 in 2015, indicating intensive influences from human activities on coastlines. By examining coastal zones, a variety of large-scale marine industries (e.g., the shipping and electric power industries) were observed to emerge successively in Xiangshan Harbour in recent years, resulting in the increase of the integrated coastline utilization index. In 2015, the proportion of constructed coastline to the total coastline in the harbor reached 18.0%, and the harbour's integrated coastline utilization index was 0.53, which was the highest in all coastline sections in Zhejiang Province. The integrated coastline utilization indices of the Jiaojiang Estuary and North Beach in Hangzhou Bay maintained a higher than average value for the coastlines in Zhejiang Province throughout the study period, reaching 0.42 and 0.39 in 2015, respectively. This was caused by a high-intensity development in coastal zones. Specifically, the Jiaojiang Estuary witnessed a large-scale sea reclamation, as well as industrial and transport development. The North Beach was mainly developed into harbour coastline dominated by the Jiaxing Port and different harbor industries. The integrated coastline utilization index of South Beach in Hangzhou Bay fluctuated seriously, which was a response to the integrative effect of sedimentation and sea reclamation. The rest of the coastline sections were viewed as low-intensity development sections, as their integrated coastline utilization indices were lower than the average value of all coastline sections in Zhejiang Province.

Recently, coastal zones are facing more and more problems and threats from intensive artificial activities (e.g., agricultural and fishery development, sand extraction, and exploitation of tourism resources) and natural environmental changes (e.g., climate change, sea level rise and inflows, and sediment reduction). Unlike the large-scale coastline movement toward sea areas in China, beach erosion is an universal threat to global coastal zones [38]. Under the background of global coastline recession caused by climate change and sea level rise, the mainland coastline in China is moving seaward, due to intensive sea reclamation. China has had four climaxes of sea reclamations since the foundation of the new People's Republic of China [39]. The first three climaxes were sea reclamation for salt extraction in the beginning of the foundation of the new People's Republic of China, the sea reclamation for farmlands from the 1960s to 1970s, and the sea reclamation for aquaculture from the 1980s to 1990s. The fourth reclamation's tide started with the international financial crisis in 2008. The governments highly advocated for port economy and sea-bordering industries. Thus, many unprecedented large-scale sea reclamation projects were implemented, leading to the coastline continuously expanding seaward quickly in recent years.

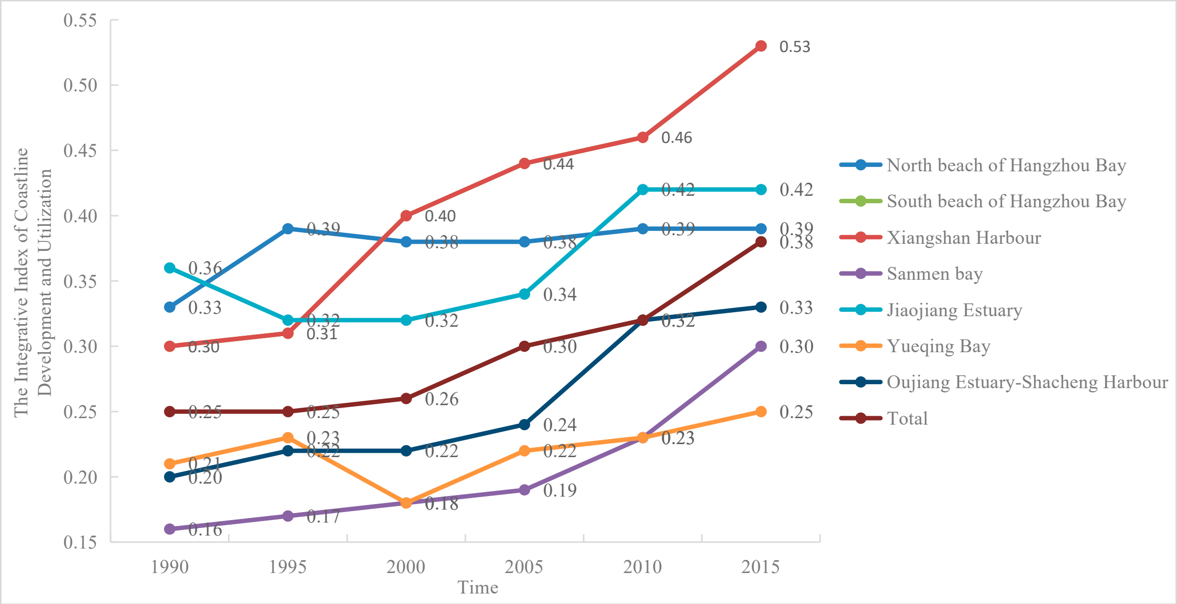


Figure 10. The integrative index of the development and utilization of the coastlines in Zhejiang Province from 1990 to 2015.

Due to the complicated and diversified coastal zones in China, coastline changes have prominent uniqueness and complexity, and thus have attracted lots of scholars' attention. In terms of the perspective of promoting and supporting comprehensive coastal management in China, future studies on coastline changes shall focus on quantifying the coastline variation trend in different coastline sections, using innovative technologies and methods for evaluating the influences of coastline changes on current and future ecological environment, economy, and society, and on increasing attentions of decision makers and managers to prevent disasters caused by coastline changes. Ultimately, the aim is to provide information and knowledge for scientific planning and development of coastal zones in China.

5. Conclusions

Mainland coastline vector data in Zhejiang Province from 1990 to 2015 were collected using RS and GIS techniques. Basic spatiotemporal change characteristics (i.e., coastline length, range, and fractal dimension) of coastlines in Zhejiang Province were analyzed. Intensity changes of coastline utilization in Zhejiang Province from 1990 to 2015 were discussed by introducing the artificialization index and subjectivity of coastline utilization. Finally, spatiotemporal change patterns of integrated coastline utilization index in Zhejiang Province were analyzed. Some conclusions, which may be used in other coastlines in China or even in rest of the world, were derived from this study as follows:

(1) The coastline in Zhejiang Province showed distinct spatiotemporal changes since 1990. The total coastline length decreased continuously. Unlike the global coastline recession, positions of the coastline in Zhejiang Province moved seaward at a dramatic rate, which were caused by many intensive sea reclamation projects. The overall coastline changed slightly, and the intensity of change was only −0.21%. The coastlines were zigzagged and had complex structures, due to

the mountainous and hilly topography. The average fractal dimension of mainland coastline in Zhejiang Province during the last 25 years was 1.0922. It was relatively stable before 2000, but decreased continuously later on. This was caused by the increasing human activities that decreased coastline curvature and complexity. The fractal dimension of the coastline in 2015 decreased to 1.086, which directly reflected the high intensity of the coastline artificialization in Zhejiang Province.

(2) The fractal dimensions of the coastlines in North Beach and South Beach in Hangzhou Bay, as well as Xiangshan Harbor, were generally lower than the overall fractal dimension of the entire coastline in Zhejiang Province throughout the study period. Sanmen Bay presented the highest fractal dimension which was maintained over 1.14 from 1990 to 2015. The fractal dimensions of the coastlines in Jiaojiang Estuary, Yueqing Bay, and Oujiang Estuary-Shacheng Harbour were slightly higher than the average value, and they fluctuated gently.

(3) The artificialization index of coastline in Zhejiang Province increased continuously during the study period. The major artificial activity was developing bedrock coastline in the harbour areas. In sludge coastal zones, the artificialization index decreased slightly, due to the excessive sedimentation compared to sea reclamation intensity. In particular, North Beach in Hangzhou Bay, Xiangshan Harbour, and Jiaojiang Estuary showed the highest artificialization index, followed by South Beach in Hangzhou Bay and Jiaojiang Estuary-Shacheng Harbour (0.37 and 0.46, respectively). Sanmen Bay and Yueqing Bay achieved the lowest artificialization index.

(4) There was a single principal coastline utilization type in South Beach in Hangzhou Bay, Sanmen Bay, and Oujiang Estuary-Shacheng Harbor. The Xiangshan Harbour maintained a binary coastline structure composed of bedrock coastlines and aquaculture coastlines. The coastline utilization structure in Jiaojiang Estuary evolved from a binary structure to a ternary structure, then back to binary structure again. The coastline utilization structure in North Beach in Hangzhou Bay evolved from the ternary structure to a single structure, and then back to the ternary structure again. The coastline utilization structure in Yueqing Bay also evolved from the binary structure to a single structure, then back to the binary structure again.

(5) The integrated coastline utilization index in Zhejiang Province kept increasing during the study period, indicating the continuous intensive influences of human activities on coastlines. The Xiangshan Harbor achieved the highest integrated coastline utilization index compared to the rest of the coastline sections in Zhejiang Province, and reached 0.53 in 2015, which was mainly caused by marine industries. The integrated coastline utilization indices of Jiaojiang Estuary and North Beach in Hangzhou Bay, which were 0.42 and 0.39, respectively, in 2015, were higher than the average value in Zhejiang Province. These three coastline sections were evaluated as the high-intensity development sections. The integrated coastline utilization index of South Beach in Hangzhou Bay fluctuated violently, which was a response to the integrative effects of sedimentation and sea reclamation. The remaining three coastline sections were viewed as the low-intensity development sections, due to the low integrated coastline utilization indices.

Acknowledgments: The study was supported by NSFC-Zhejiang Joint Fund for the Integration of Industrialization and Informatization (No. U1609203), Natural Science Foundation of Ningbo, China (No. 2017A610300) and the K.C. Wong Magna Fund of Ningbo University.

Author Contributions: Jialin Li, Mengyao Ye, and Ruiliang Pu designed the research and wrote the paper. Yongchao Liu, Qiandong Guo, Baixiang Feng, Ripeng Huang and Gaili He analyzed the data.

Conflicts of Interest: The authors declare no conflict of interest.

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