Research Article

A Spatiotemporal Change Detection Analysis of Coastline Data in Qingdao, East China

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This study focuses on the coastal features, environments, and dynamics to accurately describe and regularly monitor the Qingdao shoreline in eastern China. It collects categorical ETM+ and OLI data from 2000, 2010, and 2019 on the mainland coastline and explores the characteristics and spatiotemporal differences across the past 19 years by using remote sensing and geographic information system (GIS) technologies. The results show that the length of the Qingdao coastline has increased continuously over the last two decades, for a total increase of 18.14 km. There are different natural and artificial coastlines that have undergone major changes. The human-induced deterioration of coastlines has gradually and substantially risen from 53.63% in 2000 to 68.40% in 2019, while the length of the natural coastlines has decreased dramatically. Jiaozhou Bay focuses on areas with significantly changing coastlines, and major changes have occurred in the west and east of the Qingdao coast. The coastline has largely expanded seaward because of the comprehensive impact of natural and anthropogenic factors. The leading factor in coastal evolution is coastal engineering constructions. In addition, the top three other construction activities are the restoration of the aquaculture pond, salt field, and harbor edifices. The driving force that triggered the shift in the coastline reveals significant temporal heterogeneity.

1. Introduction

The coastline makes up the border between sea and land contact [1], a significant human survival and growth base and carrier, and a special natural resource [2]. Instability [3–7], functional diversity [8], geographic disparity [9, 10], and other significant features are included in these characteristics. Coastal countries have converted their economic growth centers into coastal areas since the twentieth century, and almost 50% of the world's population has settled in areas within 100 km of the coastline [11]. More emphasis is focused on coastal changes as they are major environmental

factors that directly affect coastal economic growth and land management [12, 13]. The relocation of economic centers, however, has triggered rapid changes in coastal resources, which have had an immense effect on the economic, social, environmental, and ecological aspects of coastal areas [14]. For instance, the proportion of natural coastlines has been significantly reduced by large-scale reclamation projects [15]. The biological ecosystem of coastal areas has been degraded by the intensive use of coastlines, artificial correction of naturally curved coastlines, and disorderly aquaculture. The coastal zone has become a crucial region for coastal economic growth with the continual development

of marine resources. An efficient way to research the environmental and ecological changes of the coastal zone is to track coastline changes. Nayak [16] suggested that, for understanding different coastal processes, detailed demarcation and monitoring of shorelines (long-term, short-term, and seasonal) are important. Coastal monitoring has therefore become an important activity for sustainable development and the conservation of the environment [17, 18].

Because of their high coverage and low cost, remote sensing (RS) image-based methods have now become popular for monitoring coastline changes [19–25]. Many scientists have documented changes to the coastline, and the causes of these changes have been investigated and recognized [26]. For instance, through the use of open-access multitemporal satellite imagery, Mishra et al. [27] evaluated the long-term to short-term dynamics of the coastal position of the Uri district in India over the past 25 years (1990–2015), deriving the explanation behind the changes such as human buildings and coastline erosion. Kale et al. [28] researched the erosion rates and coastal variations on the Yesilirmak River on the northern coast of Turkey before 2017 to clearly demonstrate the effect of dam buildings on the data. Thoai et al. [29] studied the changes in the coastline of the Ca Mau Cape in Vietnam over the past 20 years and concluded that forest area loss, river dredging, and aquaculture and infrastructure growth were the most significant factors influencing the changes in the coastline in the region. Wu et al. [30] took China's Shenzhen Special Economic Zone as an example to study coastline changes in the region from 1988 to 2015 and found that coastline stability characteristics were entirely different between the eastern and western coastlines of Shenzhen, with regional differences primarily reflected in morphological changes and changing coastline laws.

Researchers around the world performed their studies mainly from two viewpoints on coastline changes: (i) measuring rates of coastline shift and shifting areas of land or sea to describe coastline spatiotemporal variability [31–36]; (ii) based on a study of spatiotemporal trends of coastal changes, the exploration of the impact of geology, geomorphology, climate, and economy on coastline changes [37–40]. Many research studies on improvements to coastlines have been performed. However, the coastline derived from satellite images by several processing methods [24, 41–43] is the land-sea boundary that existed at the particular time of the acquisition of the image, namely, the instantaneous coastline [44, 45], rather than the actual geographical description of the coastline [46–48]. It is important to transform this instantaneous coastline into a tide-coordinate coastline [44]. Unless adequate ground control and photogrammetric coverage are available, this approach has restricted use for historical coastline determination [49].

In different countries, the use of remote sensing and geographic information system technologies to track changes in the coastline has become the focus of much scholarly study. The integration of the two technologies is seldom explored in many studies. The challenge of collecting data over a long-term period is one explanation for this. Other explanations are that several extraction rules have been used to extract the coastline for remote sensing details, and the extraction process is complicated. Most researchers study the coastline, or coastal region, and its driving powers. Therefore, based on five remote sensing images of Qingdao from 2000 to 2019, this study uses a visual interpretation method to extract remote sensing information of the coastline. Quantitative analysis of the Qingdao coastal long time series of different spatiotemporal evolution characteristics and response relationship is conducted. The research findings can provide basic data for the production and use of coastal protection and coastal zone and are of great importance for solving the coastal zone health ecosystem problems.

1.1. Study Area.
Qingdao is in the southeast of the Shandong Peninsula, at 119°30′–121°00′ east longitude, 35°35′–37°09′ north latitude, bordering the Yellow Sea in the east and south, next to Yantai city in the northeast, bordering Weifang city in the west, and bordering Rizhao city in the southwest (Figure 1), a total area of 11,282 km² [50].

2. Materials and Methods

2.1. Database.
Landsat multitemporal satellite data (Operational Land Imager-OLI and Enhanced Thematic Mapper Plus-ETM+ sensors) with a spatial resolution of 30 m are used in the research work to cover the area of the study in 2000, 2010, and 2019. The images were collected from the EarthExplorer website (http://earthexplorer.usgs.gov) of the US Geological Survey (USGS), all of which were rectified and projected with a geographical error of 0.5 pixels using the Universal Transverse Mercator method in the World Reference System (WGS84) results. Table 1 depicts the details regarding the data.

2.2. Extraction and Classification of Qingdao Coastline.
First, in this research paper, the preprocessing steps, including atmospheric correction and radiometric correction stages, have been applied to satellite images using ENVI 5.3 software. ArcGIS 10.5 was used for the classification of coastlines. The method of coastline interpretation includes visual interpretation and automated remote sensing image interpretation [51]. Methods of automatic analysis, such as the edge detection algorithm, the mathematical morphology algorithm, the region-growing algorithm, the data mining method, and the neural network method proposed in recent years, are widely used around the world, but conventional methods, such as the visual interpretation of human-computer interaction, are still widely used by experts to extract coastal information [52]. The method of human-computer integrated visual perception was therefore adopted in this article. ENVI 5.3 [53] software was used to preprocess the remote sensing images, including hypercube fast line-of-sight atmospheric analysis (FLAASH), radiometric correction, image registration, and different scene image mosaics. Most of the images were corrected systematically and geometrically. After preprocessing, the remote sensing images were separated by the normalized difference water index (NDWI) [54], the boundary line was enhanced, and the exact location of the instantaneous water edge was
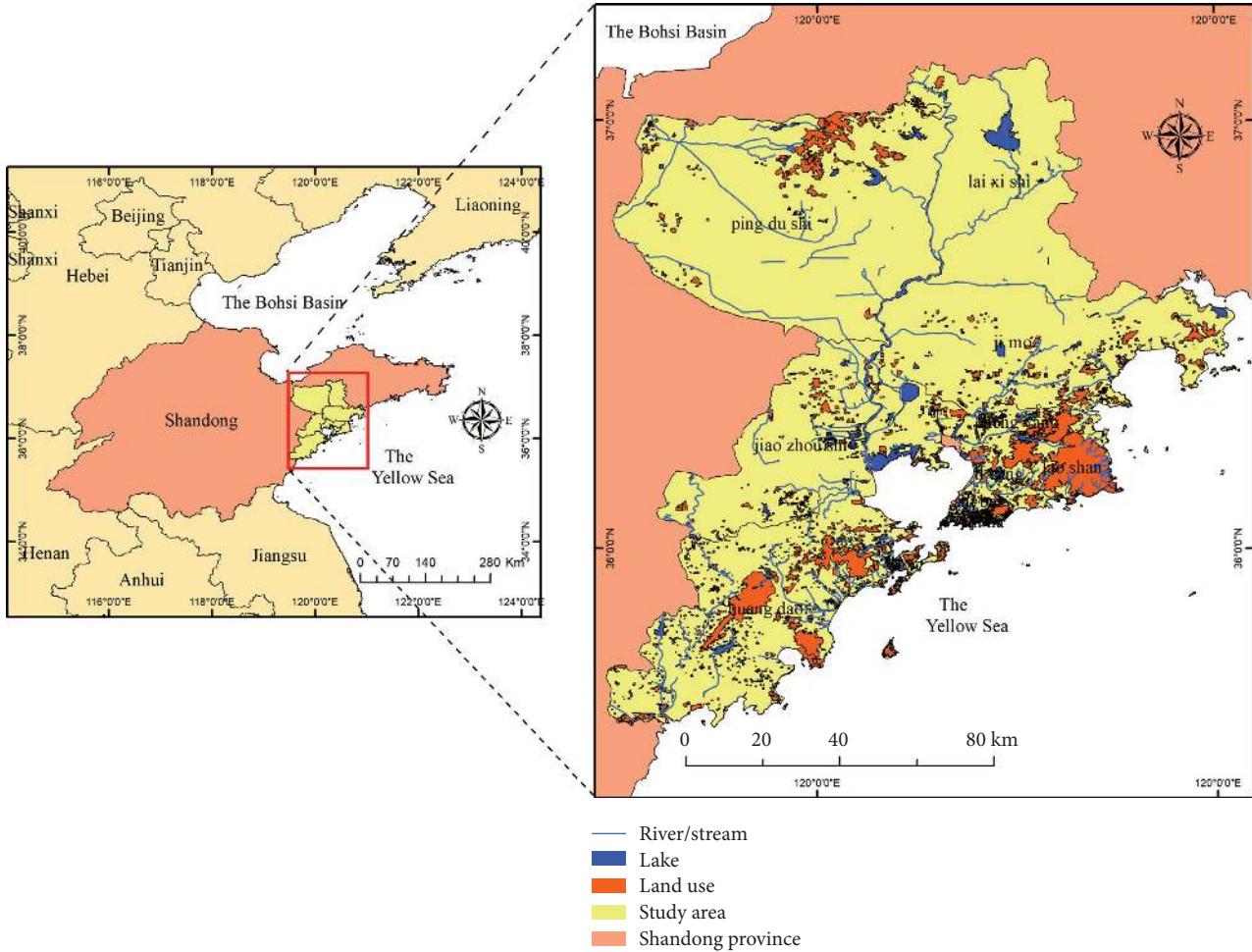
FIGURE 1: Geographical location map of Qingdao and shoreline, East China.

TABLE 1: Data source and its specifications.

Year	Satellite	Sensor	Path/row	Date	Resolution (m)	Cloud	No. of bands	Format
2000	Landsat_7	ETM+	120/35	08/9/2000	30	0	7	Geo TIF
2010	Landsat_7	ETM+	120/35	29/10/2010	30	0	7	Geo TIF
2019	Landsat_8	OLI	120/35	29/9/2019	30	0	11	Geo TIF

obtained by Otsu's threshold segmentation method based on the clarification of the characteristics of the differential reflection spectrum near the coastline [55]. The classification of the coastline acquired was mainly based on information gained from Google Earth images and field surveys; subsequently, topographical map digitization and visual analysis of remote sensing images were categorized. The coastlines were divided into coastlines on the island and coastlines on the mainland, and we only examined the mainland coastlines in this article.

2.3. Accuracy Validation of Extracted Coastlines. To test the accuracy of the extracted coastline, the statistical method of manually choosing random points was used [56]. First, on the initial image along the edge of the coastline, we manually picked 900 points. For each data cycle, we selected 900 points,

for 2700 points for accuracy evaluation. Then, from each random point to the extracted coastline, we determined the shortest distance. The distance value was positive if the random point was within the land; otherwise, it was negative. The image resolution of TM/ETM+ and OLI was 30 m (Table 1). Therefore, according to the statistical results of the histogram (Figure 2), the proportions of random points chosen in 2000 within a one-pixel distance were 87.55% in the three cycles of 2000, 2010, and 2019, 90.78% in 2010 within a one-pixel distance, and 94.45% in 2019 within a one-pixel distance, and the extraction results were satisfactory.

3. Results

3.1. Classification of Coastlines. The distribution of coastal types for the years 2000, 2010, and 2019 was obtained through the acquisition and subsequent analysis of images of
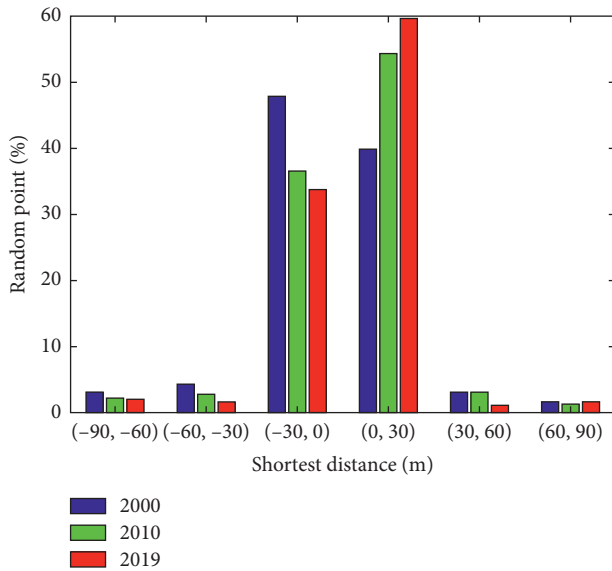
FIGURE 2: Histogram of randomly selected reference points (%) and the shortest distances (m) to the extracted coastlines.

the coastal areas of Qingdao covered by remote sensing satellites over the past 19 years. The Qingdao coastline was split into natural coastlines and artificial coastlines based on detailed research findings [3, 57–60]. The natural coastlines were divided into bedrock coastline, sandy coastline, muddy coastline, and estuaries; furthermore, the artificial coastlines were divided into harbor and wharf, revetment and seawall, aquaculture, and salt field. On the Landsat images, the corresponding coastline was shown in 543, 432, and 321 bands combined with false color displays (Figure 3), and finally, the coastline classification was achieved through interactive visual representation between humans and computers. Detailed classification information is shown in Table 2.

According to the statistics of the coastline classification results shown in Table 3 and Figure 4 the total length of Qingdao's coastline in 2000 was 507 km, of which the total length of the natural coastline was 235.22 km, and the total length of the artificial coastline was 272.34 km. As shown in Table 3, from 2000 to 2019, because of the comprehensive effects of natural and anthropogenic factors, the total length of coastlines in Qingdao increased by 4.35% in which the rates of change in 2000–2010 and 2010–2019 were 2.01 and 2.29, respectively, with a trend of accelerating growth. Anthropogenic variables influenced the coastline of Qingdao from 2000 to 2019. The total length of artificial coastlines increased from 272.34 km in 2000, accounting for 53.63% of the total length of the coastline, to 359.81 km in 2019, accounting for 68.40% of the coastline (Figure 4(a)).

The length of the natural boundary lines quickly decreased from 235.52 km to 180.15 km and then decreased steadily to 166.19 km. On the opposite, the length of the artificial boundary line grew quickly at first and then increased steadily. In 2019, its size grew to 526 km from 507.86 km in 2000. Throughout the long coastal region of Qingdao, bedrock has continuously deteriorated along the natural coastline

(Figure 5). From 2000 to 2019, the bedrock coastline was substantially reduced from 29.04% to 13.65% by proportion. The sandy and estuarine coastline types have probably shown a growing pattern from 2000 to 2019 over the entire period. The muddy coastline was the only form of coastline where no change was observed overall. The largest altered portion among the artificial coastlines was aquaculture, followed by revetment and seawall (Figure 5). The area of the aquaculture coastline grew steadily over the entire period from 2000 to 2010, but its length decreased between 2010 and 2019. In the entire time from 2000 to 2019, harbor and wharf have progressed along the entire coastline. The salt field was the only coastline that proportionally showed a declining trend in its duration from 2000 to 2019, and it was 7.43% to 4.64%. Construction showed a decreasing trend from 2000 to 2010, but it increased rapidly after 2010. Despite the fact that the seawall and revetment only cover a small portion of the total coastline, their growth rate accelerated after 2000, and they were particularly visible from 2010 to 2019. In Figure 5, the spatial distributions are shown.

4. Discussion

A complicated interaction of different human-induced and natural coastal processes triggers the shoreline changes. The shorelines are changed by natural processes because of geology and geomorphology, the cumulative motion of tides and winds, sea level fluctuations, tectonics, and storms. Manipulation of hydrological cycles by dam construction, building on beaches, coastal structures such as harbors, beach-protecting structures, jetties, mining of beach sand, and degradation of coastal vegetation are the human activities that could exacerbate coastal changes. Most of the anthropogenic growth was the key reason for the coastline change in Qingdao over 19 years, while the natural factors were the secondary reasons [50]. The overall changes of shorelines along the coast of mainland China increased over the ~1990–2019 period primarily for land reclamation and quay construction [61].

Climatic conditions and natural processes are important in determining shoreline changes. These processes are influenced not only by changes in tides, waves, etc., on an hourly or daily basis but also over longer timescales, such as sea level and climate change. Relative sea level rise, which may occur because of a rise in the water volume of the seas or the subsidence or emergence of land by natural processes, is a long-term geological phenomenon of paramount significance to the shoreline. In the Qingdao coastal zone, the relative change in the sea level might be involved in modifying the shorelines. Over the past decades, the length of natural shorelines of each subtype has decreased, while artificial construction and quay shorelines of the artificial group have increased dramatically [61].

The shoreline changes have included different coastal landform features such as headland and bays, mudflats, estuaries, beaches, and bedrocks in the study area. The present study shows that the coastal areas of the bedrocks are under significant threat of decline. More changes have occurred in the narrow continental shelf and exposed rocky

Figure 3: Rocky coastline (a, b), sandy coastline (c, d), estuarine coastline (e, f), and artificial coastline (g, h) superimposed on Landsat (2019) and Google Earth images (2019).

coast regions, resulting in the accumulation of sandy and muddy sediments along beaches and estuaries. More sediments are produced, and cliffs are created by the high wave energy acting on the soft part of the bedrocks, which eventually changes the shoreline along the entire study area.

In the present results, rocky shorelines were lost, which evinces how anthropogenic changes that are often extreme

to local ecosystems will destroy natural environments and prevent the accessibility of future generations from experiencing these lively, living landscapes. Sand deposited along the beaches is for the influence of materials transported by continental rivers and waves [62]. Coastal shifts have also been witnessed by low-lying sandy beaches and dunes, resulting in an overall seaward rise along the shoreline. The

TABLE 2: The coastline classification system of Qingdao, East China.

Primary categories	Secondary categories	Classification definition	Location name
Natural	Bedrock boundary line	It is the demarcation line on the bedrock coast between the land and sea	Liuqinghe
	Estuary boundary line	The border between the ocean and the estuary and between the ocean and the river	Mengjiatan
	Sandy boundary line	Composed of loose, very soft, and fine materials such as sand, silt, and sludge; comprising relatively straight coastline and wide, long beaches; sand in the bay at high tide	Jinshatan
	Muddy boundary line	Coastline on the muddy or silt coast, which is usually at the vegetation line where salt-tolerant plant distribution patterns change	Wangtai
Artificial	Salt field boundary line	The saline-alkali drying sea-land dividing line	Taitou
	Construction boundary line	A land-to-sea demarcation line for the growth of the maritime industry and for other constructions	Suliu
	Harbor and wharf boundary line	A demarcation line for the practical usage of port terminals between the land and sea	Xiangyang
	Breeding boundary line	An artificially built land-sea border for aquaculture	Yinghai
	Road boundary line	The land-sea dividing line of the artificially built highway	Xiaozhuang
	Other artificial boundary lines	Lines of artificial boundaries, which do not belong to the classification above	

Modified from [3, 57–60].

TABLE 3: Qingdao coastline statistics for 2000, 2010, and 2019.

Coastline types	2000		2010		2019		Net change area (%)	
	Area (km)	Area (%)	Area (km)	Area (%)	Area (km)	Area (%)	2000–2010	2010–2019
Natural coastline								
Bed rock	147.49	29.04	86.55	16.70	72.35	13.65	12.34	3.05
Sandy	80.64	15.87	88.15	17.01	88.74	16.74	1.14	0.27
Muddy	3.81	0.75	—	—	—	—	—	—
Estuary	3.58	0.70	5.45	1.05	5.10	0.96	0.35	0.09
Subtotal	235.52	46.37	180.15	34.77	166.19	31.35	11.6	3.42
Artificial coastline								
Aquaculture	117.19	23.07	167.01	32.23	137.29	26.08	9.16	6.15
Salt field	37.76	7.43	31.87	6.15	24.51	4.62	1.28	1.53
Construction	21.82	4.29	16.87	3.25	35.71	6.92	1.04	3.67
Harbor and wharf	31.34	6.17	55.72	10.75	66.18	12.67	4.58	1.92
Revetment and seawall	64.25	12.65	66.46	12.82	96.12	18.32	0.17	5.5
Subtotal	272.34	53.63	337.93	65.23	359.81	68.65	11.6	3.42
Total	507.86	100	518.08	100	526.00	100	—	—

Qingdao coastal zone has headlands and bays, which result in changes in the shoreline along the coast. There are few areas with curved sandy beaches and multiple estuaries that easily trap the sediments and contribute to the shoreline changes. Coastal plains are often formed depending on the rivers and their catchment area [63]. Development and its associated sedimentary processes have been and are some principal contributors to coastal geomorphology in much of the coastal region. The deposition of sediment shapes coastal features such as beaches, mudflats, estuaries, mangroves, and sand dunes. During 2000–2019, the Qingdao coastal region has experienced more accretion for the excess amount of sediment discharged through the rivers [47]. Sediment discharges from rivers are considerably reduced due to the building of dams, infrastructures, development activities, and encroachments (Figure 3). This makes the sandy beaches along the shoreline more vulnerable to destruction.

Ocean waves are one of the prime movers for the littoral processes which bring changes along the shoreline. For example, the greatest factor affecting the evolution of the shoreline shift is the long-shore sediment transport rate [64]. In the formation of such coastal features, such as bars and spits, coastal transport plays a major role and causes substantial shoreline changes [65]. The coastal zones of Qingdao have experienced changes because of the littoral drift of sediments transported through the Yang, Feng, Long Quan, and Wu Long Rivers. Most of the rivers have failed to develop true deltaic characteristics because of the strong offshore current in the study area.

Human interventions and anthropogenic activities have a major influence on shifts in shorelines. Consistent with previous researchers [3, 66], the key driving force behind the shoreline changes was human activities, including land reclamation [67–69], aquaculture development [60], and
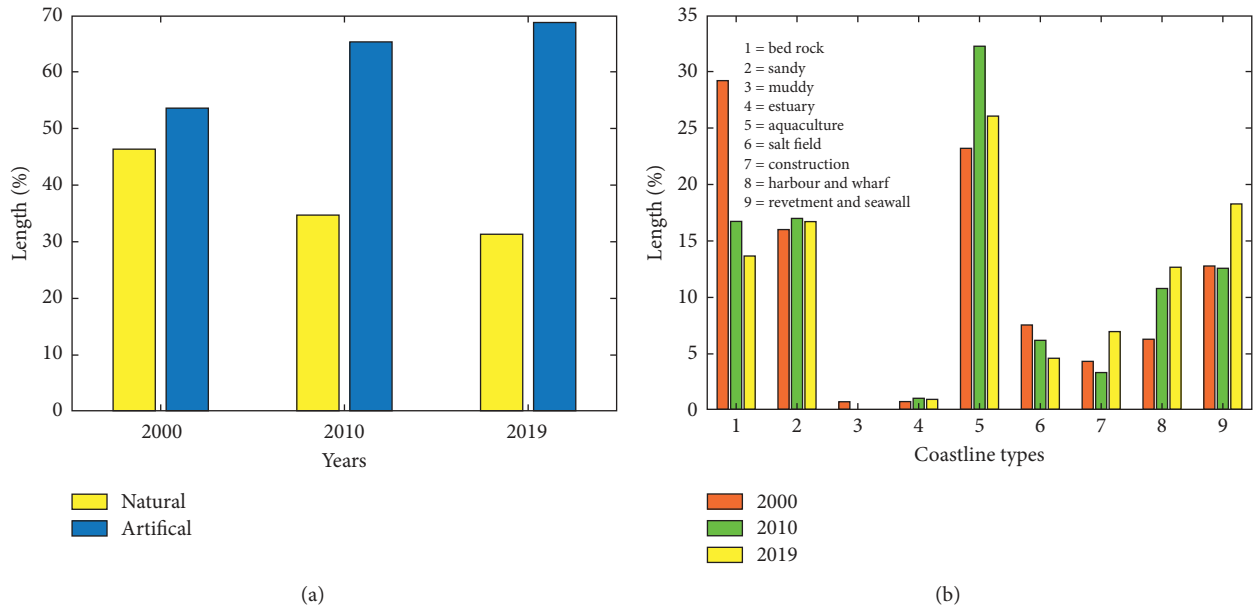
FIGURE 4: (a) Artificial and natural coastline length (%) from 2000 to 2019 and (b) percentage of different coastline lengths from 2000 to 2019 of Qingdao coast.
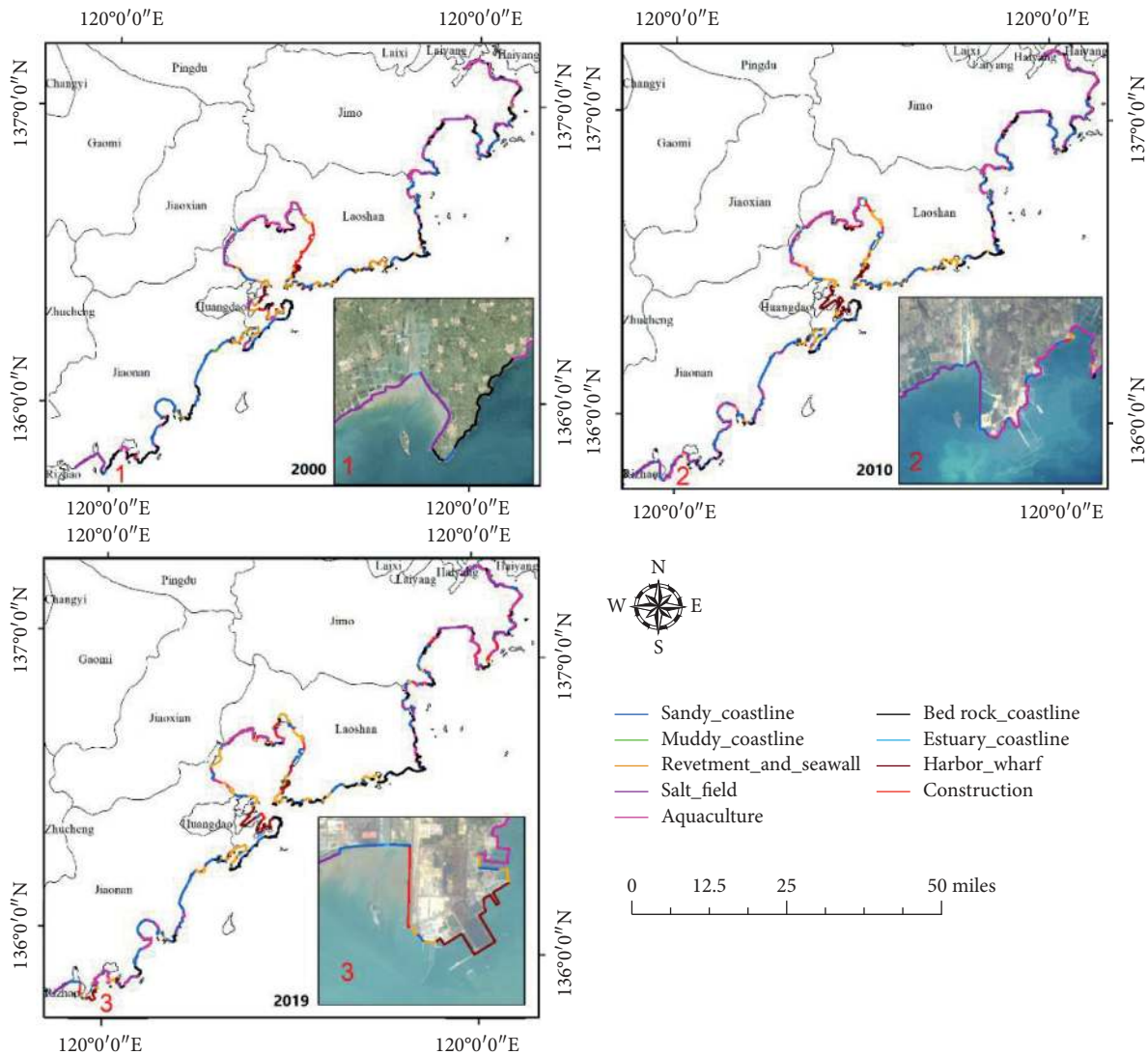

FIGURE 5: The spatial distribution on the Qingdao coast of the secondary coastlines.

quay construction [70]. The shoreline morphology also results in coastal urbanization, extraction, shifting of coastal sands, and dredging. The reduced supply of sediment caused by offshore sand mining, shoreline disturbances, and damming of sediment-rich rivers has led to the further loss and deterioration of coastal ecosystems, including beaches, estuaries, and mudflats.

The construction of coastal structures such as seawall, revetment, harbors, wharf, and aquaculture in Qingdao coastal regions may interfere with the process of long-shore drift, changing the sediment budget and exacerbating shoreline changes of the adjacent bedrocks, estuaries, mudflats, beaches, or beach head in a down-drift direction. The current study shows that, for anthropogenic processes along the coast, the Qingdao coast undergoes greater changes. Shoreline changes are exacerbated by unsustainable coastal construction programs. Different construction works are carried out along the shore that can cause major changes in the surrounding shoreline coastal area. The present studied coast of Qingdao is heavily experienced by constructions, revetment, seawall, and aquacultural activities (Figures 3(g) and 3(h)). Because of anthropogenic activities, this coast has high change rates, and it discloses the fact that the existence of river input, salt fields, and wave patterns determines the rate of shoreline changes. The disruption of river input is apparent here, which results in the beach's direct risk of survival.

There are several factors such as sand dunes and vegetation which protect shorelines from changes and help to preserve the coastal environment. The human-induced activities that cause shoreline changes have significantly affected these natural protections. Tian et al. [61] mentioned in 2020 that low-economic value shorelines, such as rocky, sandy, muddy, and estuarine shorelines, were transformed into high-economic value shorelines, such as aquaculture, which were transformed into shorelines with even more economic values, such as shorelines of construction and quay. Growing populations and development works along the coasts put the coastal ecosystems under unprecedented pressure. Meanwhile, ongoing manifestations of climate change, such as increasing sea levels and the severity of storm surges, increase the threats to the coastal population's habitats, natural resources, infrastructure, and well-being.

5. Conclusion

In this study, Landsat ETM+ images for 2000 and 2010 and Landsat OLI images for 2019 are used to delineate and classify the coastline along the East China coast of Qingdao. Because of both natural and human-induced activities, the Qingdao coastal zone has undergone significant coastline modifications. The spatial and temporal variations of the coastline in the study area have been extensive in the past 19 years: the length of the coastline has increased substantially from 2000 to 2019. The increased types of coastline are predominantly artificial frontier lines. The current study shows that the total length of artificial coastlines grew from 272.34 km in 2000, representing 53.63% of the total length of

the coastline, to 359.79 km in 2019, representing 68.40% of the coastline. The rocky coast of the natural coastline decreased dramatically from 29.04% to 13.65% by proportion, whereas the largest portion covered by aquaculture in the artificial coastline changed from 23.07% in 2000 to 26.08% in 2019.

The growth of the coastline has been significantly influenced by human activities. The length of the natural coastal boundary line has deteriorated, converting a substantial number of natural coastlines into artificial coastlines. The geomorphological and geological effects, sediment supply, and relative increase in sea level promote shoreline development. The analysis of the shoreline change rate often shows both short- and long-term changes along the studied area's different coastal zones. Eventually, the environmental and resource shifts of the studied Qingdao coastal zone influence the coastal landforms. The types of coastal landforms change with the changes in the artificial and natural features along the coastline, particularly the infrastructure, aquaculture, harbor structures, bedrocks, beaches, estuaries, and mudflats. Human activities influence not only the shifts in the coastline but also the coastal zone's types and areas of surface coverage. A realistic management method is provided by the study of shoreline change and modes based on geomorphic concepts and thus understanding the reasons for shoreline changes. The present research thus clearly focuses on the impacts of the coastal processes produced in the study area, both natural and anthropogenic.

Data Availability

The authors used the USGS and field data along Qingdao coastline.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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