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Impact of Land Reclamation on the Evolution of Shoreline Change and Nearshore Vegetation Distribution in Yangtze River Estuary

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Abstract Land reclamation directly changes the local coastal morphology, causing potential ecological consequences. To quantify how land reclamation influences the shoreline change, we employed shape entropy, in addition to traditional parameters, including shoreline length, land area change rate, and fractal dimension, extracted from SPOT satellite images from a number of representative years throughout two decades (1987–2012) to describe shoreline changes in Yangtze River Estuary, China. The vegetation growth boundary, representing the nearshore vegetation distribution as an ecological indicator, was also extracted and compared with the shoreline result. This comparison indicated that both vegetation growth boundary and shoreline evolve in a more complex and yet more orderly pattern partly because of land reclamation. Vegetation growth boundary changes more dramatically than shoreline, due to the combined effects of agricultural development and artificial beach nourishment, as well as the alternation of tidal creeks. These results have important implications for coastal wetland conservation and utilization in regions with intensive land reclamation such as the Yangtze River Estuary.

Keywords Land reclamation · Shoreline change · Vegetation growth boundary · Shape entropy · Yangtze River Estuary

Introduction

Sea reclamation, a large-scale human disturbance to natural ecosystems, has negatively affected environment and ecosystems in coastal zone (Wang et al. 2014; Min and Kim 1999). Understanding environmental and ecological impacts of sea reclamation are critical issues that must be addressed in order to protect coastal wetlands and sustain developing economies (Peng et al. 2005; Min and Kim 1997; Mostafa 2012; Zhang et al. 2012). Variations in the shoreline, which is the connection between sea and land, are influenced directly by land reclamation, and consequently, may affect vegetation evaluation in coastal wetlands and habitat distribution (Suzuki 2003; Carl and Megan 1996; Mario et al. 2007; Min and Kim 1999). Philippe and Edwin (1999) studied benthic subtidal communities in different shorelines in the St. Lawrence Estuary (Canada), and found that community recruitment, abundance, and diversity are the lowest along straight shorelines.

Understanding the shoreline system, because it is the connection between sea and land, is fundamental for understanding the impact of sea reclamation. In order to describe the changes in the shoreline, many studies focus on shoreline length, land area, and fractal dimension (Wu et al. 2011; Kumar et al. 2010; Sharma and Byrne 2010). Kuleli (2010) employed the index of land area by calculating the end point rate (the ratio between the shoreline movements along one transect and the time span between them) to study the potential movement and changes of the coastline at the southeast coasts of the Mediterranean Sea in Turkey. Sun et al. (2013) estimated the rate of shoreline changes and the area of land changes of Hangzhou Bay, China. Faik et al. (2009) studied shoreline eroding and accreting conditions along the Vedaranyan coast by calculating the area of land changes. Benjamin et al. (2006) analyzed the fractal dimension of Maine's glaciated shoreline by using the box-counting method. Previous studies have concentrated on describing changes in the shoreline morphology by using one or two indices and have concluded that land reclamation as a reason for shoreline change.

In this study, we introduced shape entropy to describe the chaos of shoreline, in addition to describing traditional parameters such as length, land area change rate, and fractal dimension, to reflect the extent of human disturbance. Entropy is one

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of the key concepts in thermodynamics and is used to measure the chaos of a system (Anatoli 2011). In our study, we refer to entropy in the context of shape in order to measure the chaos of shoreline and vegetation growth boundary. Specifically, the higher the shape entropy value, the more disordered is the shoreline. Further, we compared the shoreline changes with variations of the vegetation growth boundary in a case study of the Yangtze River Estuary, China. We then propose suggestions for land reclamation based on the discussion of potential ecological impacts of shoreline change assessments.

Methodology

In order to understand the impacts of coastal wetland reclamation on shoreline changes, four types of indices were included to describe shoreline changes, namely, shoreline length (L), rate of land area change (V), fractal dimension (D), and shape entropy (S). As an ecological indicator, the vegetation growth boundary was also analyzed by calculating the same indices and then comparing them to the shoreline measurements.

The shoreline length is calculated based on ArcGIS analysis. Land area change rate is determined by generating polygon themes and calculated as:

$$V = \frac{\Delta A}{\Delta t} \quad (1)$$

where, $\Delta A = A_{t+\Delta t} - A_t$, A_t is the area enclosed by shoreline in the year t and Δt is the time interval of the variation.

Fractal dimension (D) was first introduced by Mandelbrot (1967). This index gives information about shoreline complexity and has been widely used in both the graphics and geography fields (Cheng 2001; Dasgupta 2013). We use fractal dimension to quantitatively describe shoreline complexity that is influenced by coastal wetland reclamation. Fractal dimension is calculated using the box-counting method (Klinkenberg and Goodchild 1992):

$$N(\varepsilon) \propto \varepsilon^{-D} \quad (2)$$

where N is the number of boxes that cover the line, and ε is the side length of the individual square boxes. The log-log form of Eq. (2) follows:

$$\lg N(\varepsilon) = -D \lg \varepsilon + A \quad (3)$$

In this study, we used box sizes (ε) of 40, 80, 120, 150, 200, 250, and 300 m.

The shape entropy we put up in this paper is calculated based on the Shannon formula in information theory (Shannon 1948):

$$S = P\ln(P) \quad (4)$$

where S is the shape entropy; $P = N^2/L$, N is the number of breakpoints, and L is the length of shoreline. In this study, we assume that breakpoints are absent from a natural coast shoreline unless it has been disturbed by human activities. The shape entropy thus can illustrate the extent of land reclamation.

Study Area

Chongming eastern beach and Nanhui District in the Yangtze River Estuary were selected as the case study area (Fig. 1). Shanghai, located on the west bank of the Pacific, along the east Asian continent, to the north of Yangtze River Estuary, is part of the alluvial plain of the Yangtze River Delta. As a city with a high level of population and economic development, the discrepancy between the lacking land resources and the population explosion in this area triggers larger and more frequent cycles of sea reclamation (Li et al. 2011).

Chongming Eastern beach is located in the eastern part of Chongming Island (Fig. 1) and is an estuarine area that continues to accumulate silt and expand under natural conditions (Wang and Zhang 2005). The ecosystem of the beach is relatively diverse, hosting an abundance of estuarine zoobenthos and vegetation communities. The bench also provides critical habitat for migrant birds in the Asian-Pacific region and serves as an important wintering area for waterfowl (Liao et al. 2010).

Under continuing demand for land resources, various types of land reclamation have been used to retain the sand and to

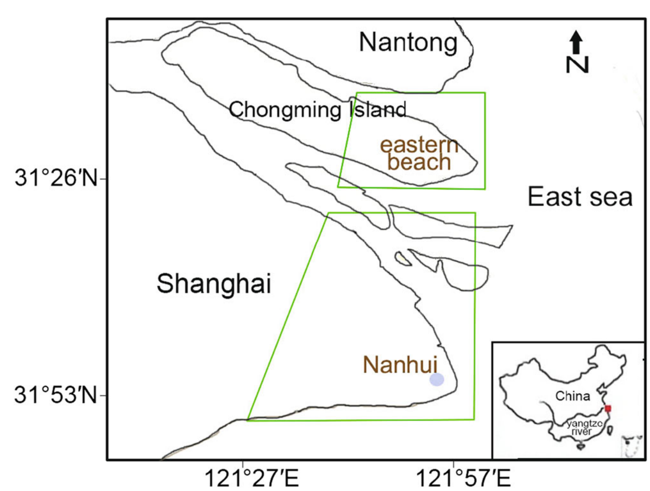

Fig. 1 Study area in the Yangtze River Estuary, China

promote siltation on the beach (Li et al. 2011). Agriculture and aquaculture are the predominant uses of the reclaimed land in Chongming eastern beach; in Nanhui District, the construction of harbors, building of landscapes and reservation of land are the main uses of land reclamation. Table 1 shows the types of sea reclamation in different years.

We extracted shoreline and vegetation growth boundary based on the data collected by the SPOT satellite with a spatial resolution of 20 m in 1987, 1995, 2002, 2008, and 2012. We define shoreline as the location of the mean high water spring tide. Silty coast, instead, was defined as instantaneous waterline. The changes of shoreline and vegetation growth boundary are shown in Fig. 2.

Results

Variations on Length of Shoreline and Area Change Rate

The changes of shoreline and vegetation growth boundary length in the two study regions are shown in Fig. 3.

Generally, the shoreline lengths of both Chongming eastern beach and Nanhui District showed an increasing trend. In Chongming eastern beach, the length of the vegetation growth boundary and shoreline decreased 0.5 % in 1995 compared to 1987, and it decreased 4.2 % from 1995 to 1998. During 1987–1998, the average change rate of shoreline length was −545 m/yr, which was 0.2-fold the rate of −2671.9 m/yr observed for the vegetation growth boundary. During 1998–2012, the average change rate of shoreline was 900.9 m/yr and that of the vegetation growth boundary, 311.8 m/yr. Shoreline length was longer than the vegetation growth boundary length during 1987–1998 and was reversed between 2002 and 2012. In Nanhui District, the vegetation growth boundary fluctuated year-upon-year, whereas the shoreline length grew consistently between 1998 and 2012. Overall, however, there was no clear relationship between shoreline length and vegetation growth boundary length.

Figure 4 shows variations of area change rate of vegetation distribution and land enclosed by shoreline. In Chongming eastern beach, the shoreline and vegetation growth boundary both tended to expand northward and eastward, except during the period 1987–1995 for vegetation growth boundary and 1995–1998 for shoreline. The rate at which the vegetation growth boundary changed was negative between 1987 and 1995 due to large-scale aquaculture activities that took place on Chongming eastern beach. Indeed, the shape of the vegetation growth boundary was similar to that of the aquaculture ponds that were constructed during these periods. In 1998, the shoreline underwent erosion in comparison to its status in 1995, while the vegetation growth boundary expanded. This occurred after many aquaculture ponds were replaced by farmlands and vegetation distributed on the beach after 1998.

The difference between the maximum and minimum rates of area change was 4767.8×10^4 m^2/yr for the vegetation growth boundary, which was 2.5-fold the value associated with the shoreline. However, during 2002–2012, the rate of shoreline area change was higher than that associated with the vegetation growth boundary. In Nanhui District, the shoreline and vegetation growth boundary showed accretion, with the exception of an erosion of the shoreline between 1998 and 2002. Between 2008 and 2012, the rate of area change did not differ significantly between the shoreline and vegetation growth boundary.

Variations of Shoreline Complexity

Over the past two decades, there has been an increase in the fractal dimension of shoreline and vegetation growth boundary in both Chongming eastern beach and Nanhui District, as shown in Fig. 5. However, the rates of change were different, with average fractal dimension value change rates of 3.8×10^{-4} yr^{-1} in Nanhui District, which was 0.2-fold the rate observed at Chongming eastern beach (2.0×10^{-3} yr^{-1}).

In Chongming eastern beach, the fractal dimension of the shoreline increased over time, which is indicative of increasing complexity. However, the fractal dimension of the vegetation growth boundary continually decreased from 1987 to 2008 and then began to increase between 2008 and 2012. Additionally, the vegetation growth boundary was more complex than the shoreline between 1987 and 1998 and then became less complex than the shoreline during 2008–2012.

Table 1 The main sea reclamation types in different years in the two study area

	Study area	
	Chongming eastern beach	Nanhui district
1992–1995	Farmland reclamation	–
1995–1998	Constructing culture ponds	–
1998–2003	Farmland and culture ponds reclamation	The artificial peninsula project and Pudong international airport siltation
2003–2012	Farmland and culture ponds reclamation	Construction of harbors, landscapes building and land reserving

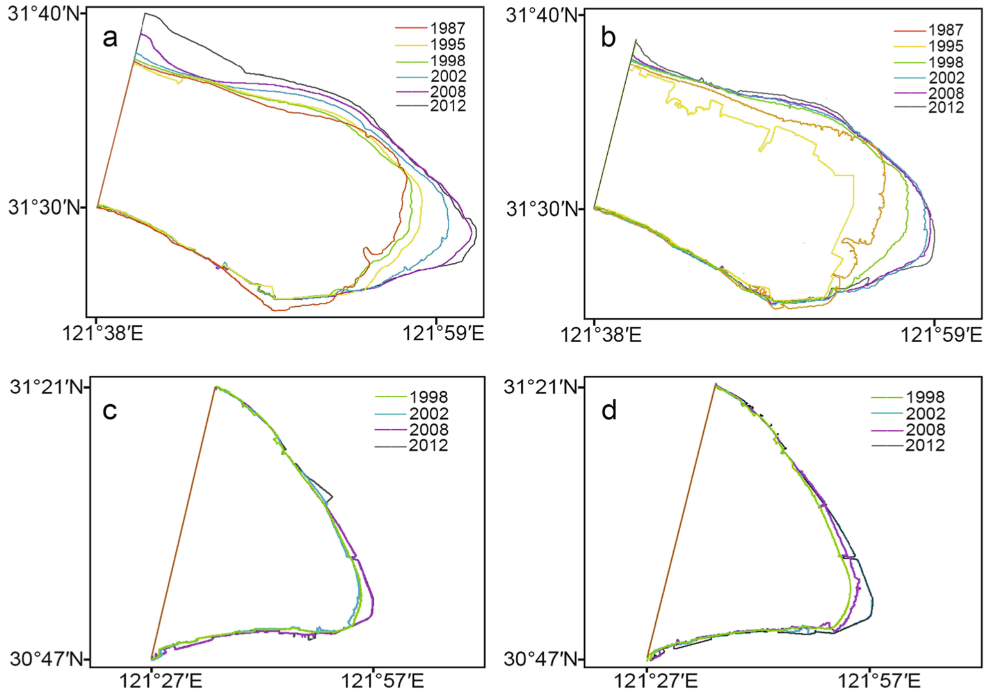

Fig. 2 Chongming eastern beach **(a)** shoreline and **(b)** vegetation growth boundary. Nanhui District **(c)** shoreline and **(d)** vegetation growth boundary

Chaos of the Shoreline is Influenced by Coastal Wetland Reclamation

The shoreline shape entropy in both regions studied tended to decrease over time (Fig. 6). The shape entropy of Chongming eastern beach shoreline decreased slightly and steadily, with an average absolute change rate of 1.3×10^{-4} yr^{-1}; this was 0.1-fold the average absolute change rate at the Nanhui District shoreline of 1.1×10^{-3} yr^{-1}.

In Chongming eastern beach, the average rate at which shape entropy of the vegetation growth boundary decreased was 2.5×10^{-2} yr^{-1} from 1987 to 1995, which was 11.4 times the average rate (2.2×10^{-3} yr^{-1}) from 1987 to 2012. This can be explained by the large-scale aquaculture activities that occurred in 1995, which transformed the shape of the vegetation growth boundary into that similar to the borderline of the aquaculture pond.

In general, it can be seen from Fig. 6 that the shape entropies of both the vegetation growth boundary and the shoreline were higher in Chongming eastern beach than in Nanhui. This was consistent with the more artificial nature of the shoreline of Nanhui District when compared to Chongming eastern beach. Although the fractal dimension of the Nanhui District shoreline from 1998 to 2012 tended to increase, the shape entropy of this shoreline decreased during this period.

Typically, the shape entropy of the vegetation growth boundary was higher than that of the shoreline; the shape entropy of Chongming eastern beach was higher than that of Nanhui District. In all cases, the measured parameters exhibited a decreasing trend.

Discussion

Variations of shoreline outside the embankments are mainly influenced by natural sediment deposition, which ultimately

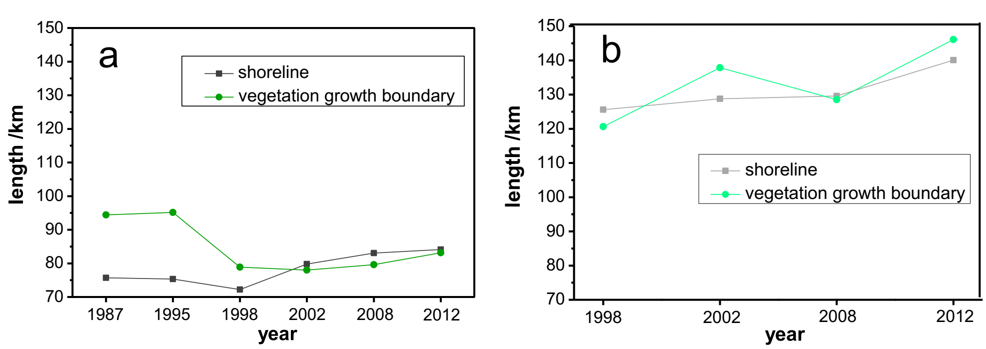

Fig. 3 Shoreline and vegetation growth boundary of **(a)** Chongming eastern beach and **(b)** Nanhui District

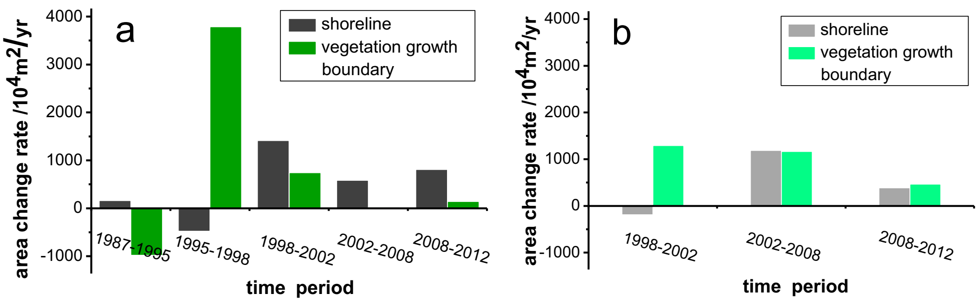

Fig. 4 Land area change rate within shoreline and vegetation growth boundary of **(a)** Chongming eastern beach and **(b)** Nanhui District

enhances shoreline complexity. The construction of embankments and large-scale aquaculture ponds disrupts this process, and therefore lowers complexity, since the vegetation growth boundary then resembles the shape of artificial structures. Correspondingly, there was a decrease in the fractal dimension of the vegetation growth boundary in Chongming eastern beach in 1998. In Nanhui District, most of the shoreline was artificial; outside this area was nude beach, where the vegetation growth boundary shape resembled that of the shoreline. The fractal dimension increased in Nanhui District, since the number of harbors and ports increased and thus contributed to the shoreline complexity. Moreover, the border of docks appears much sharper compared to a natural shoreline.

Under effects of natural sediment deposition or erosion, shoreline length and coastal wetland area may either increase or decrease, but the fractal dimension of the shoreline or the vegetation growth boundary will increase. However, anthropic factors such as land reclamations make it difficult to predict shoreline length, wetlands area, and fractal dimension changes a priori. In Nanhui District, the rate of shoreline complexity change is mainly dominated by sea reclamation activities, and in Chongming eastern beach, the shoreline complexity is mainly affected by natural factors. However, the fractal dimension value of the shoreline increased over the period studied in the two regions. Our current results indicate that evaluation of shape entropy could be employed to assess the effects of human activities on the natural shoreline. Specifically, we find that an elevated shape entropy value correlates with more severe human disturbances. The results of shape entropy analysis indicated that the vegetation boundary appeared more chaotic than the shoreline, probably because it is more likely to be affected by human activities, including the increasingly aggressive land reclamation projects.

The shape entropy analysis we proposed here is relatively simple and can be meaningfully applied when attempting to determine the chaos of shoreline and the extent of artificial disturbances. It is suitable for quantitatively describing the extent of human impact on coastal wetlands, as it estimates the chaos of shoreline systems and reflects its features at a more macroscopic scale. However, further research is required to determine the efficacy of shape entropy analysis in the assessment of the ecological impact of sea reclamation.

As a comparison between shoreline changes in different estuaries, we calculated the shoreline shape entropy of the Yellow River Estuary (Fig. 7). In 1989, the river mouth of Yellow River Estuary faced southeast. In 1996, the main channel was artificially shifted northeastward to facilitate oil drilling in the river mouth area. Owing to natural sediment deposition, the new river mouth had stretched northeastward by 5 km in 1999 (Wang et al. 2010). By 2009, the end of the channel had turned completely toward the north and the shoreline extended further seawards. Concomitant with the variations of the river mouth position, the shoreline changed as a result of natural sediment deposition, but there were no great changes to the artificial breakpoints along the shoreline each year. Therefore, we infer that the shoreline length directly affects the entropy value.

In the Yellow River estuary, artificial seawall engineering usually occurs in the north of the river mouth. Because this position is usually located inside the shoreline, there are no great entropy changes concomitant with variations of the natural shoreline in this area. The cumulative effect of erosion

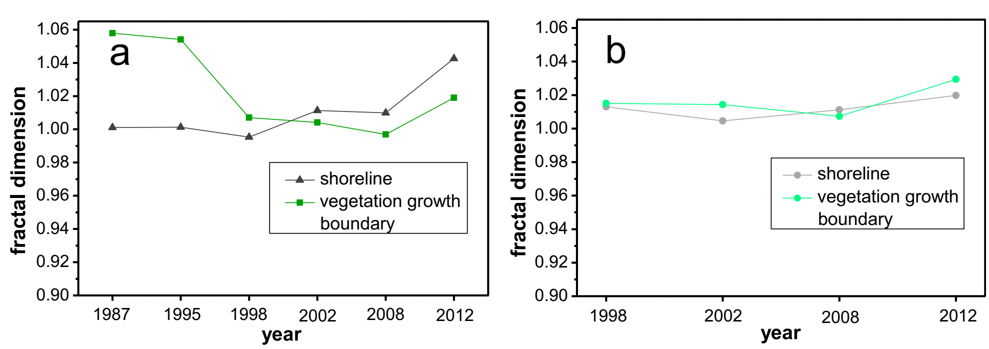

Fig. 5 The fractal dimension of shoreline and vegetation growth boundary in **(a)** Chongming eastern beach and **(b)** Nanhui District

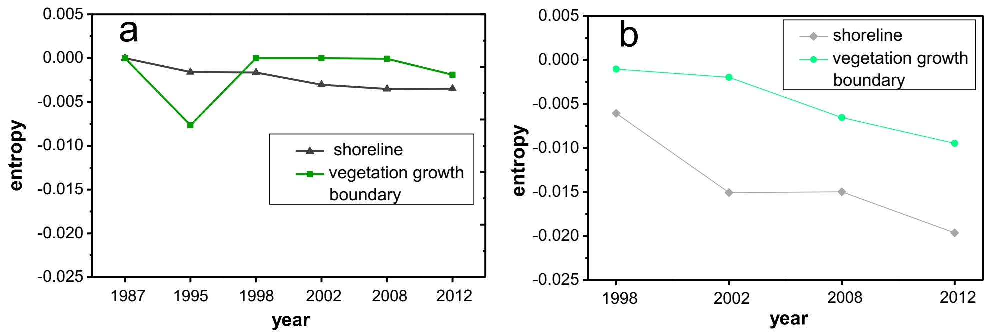

Fig. 6 The entropy of shoreline and vegetation growth boundary in **(a)** Chongming eastern beach and **(b)** Nanhui District

during 1989–2012 that was picked up by the SPOT image was likely due to the establishment of artificial breakpoints on the shoreline that could be detected after 2012. Correspondingly, the chaos of the Yellow River Estuary shoreline decreased and the extent of human impact increased in 2012 (Fig. 8).

Human impacts become more intensive in the Yangtze River Estuary due to land reclamation activities over the period studied. The impact on ecology can be reflected through the ecological index, as well as other indices, including biotic index, economic index, et al. (Melanie et al. 2012; Yu et al. 2008). A positive relation between habitat complexity and species diversity has been postulated (Abele 1974). Furthermore, Rosensweig (1995) suggested that the greater the habitat variety, the greater the species diversity. Fractal dimension is useful in describing shoreline complexity and thus can reflect habitat variety. However, whether higher fractal dimension truly indicates greater diversity of species remains controversial (Jun and Roy 1998).

As a fundamental element in the intertidal zone, there exists a connection between the shape of tidal creeks and intertidal zone ecology. Sea reclamation activities such as embanking may cut off the tidal creek and alter its development. The vegetation boundary could also be influenced by changes of the tidal creek as a result of coastal wetland reclamation. Further studies are required to classify the vegetation growth boundary by successional type. This will entail the use of images with a higher resolution in order to study the sensitivity of different ecological communities to coastal changes, and to better establish the relationship between sea reclamation, tidal creek shape, and intertidal zone ecology.

When evaluating land reclamation activities, it is better to consider the shape of the enclosed boundary. Artificial beach nourishment is also an established method that can alleviate the possible negative effects of artificial shorelines and minimize the negative impacts on ecosystems, which can be taken as an effective methods in eroding coastal areas (Henk 1992). We suggest that the fractal dimension of the edges of artificial structures that are connected to the sea should be similar to the fractal dimension of the natural shoreline. With a fixed number of breakpoints and a long shoreline, the entropy values increase. Therefore, we also suggest that breakpoints should be well dispersed along the shoreline in the regions where sea reclamation projects are undertaken.

Conclusions

In our study, the indices we chose are derived from graphics and thermodynamics. Length, area change rate, fractal dimension, and shape entropy were employed to quantify variations of shoreline and vegetation growth boundary under the impacts of land reclamation. The shape entropy index proposed here for

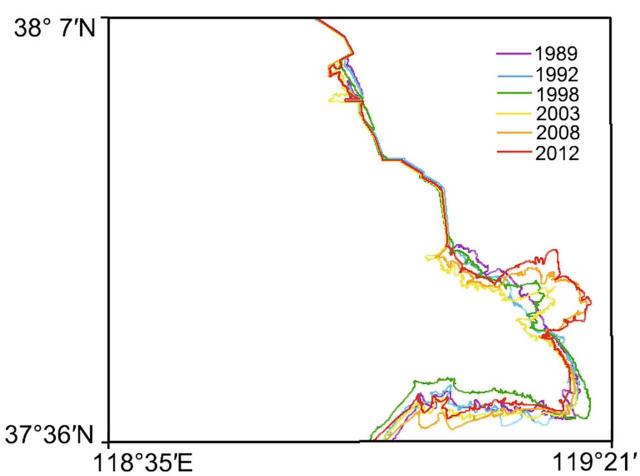

Fig. 7 Shoreline of the Yellow River Estuary

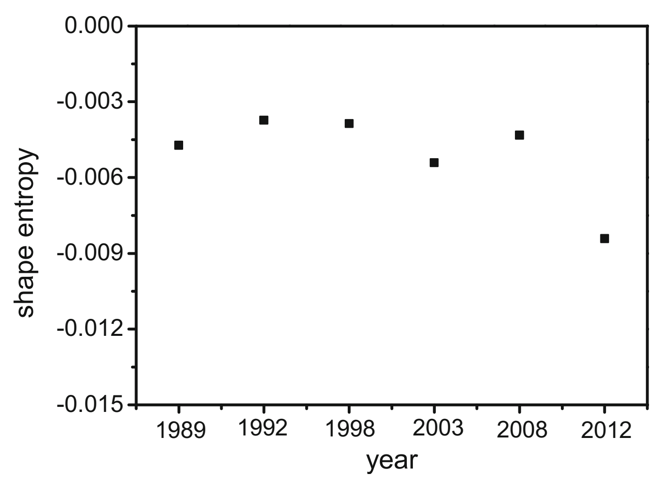

Fig. 8 The entropy of shoreline of the Yellow River Estuary

assessing variations of coastline can be applied to determine both shoreline chaos and the extent of artificial disturbance. The shape entropy of shoreline could also be taken into consideration when planning the sea reclamation activities.

Under the influence of land reclamation activities and shoreline expansion, both shoreline and vegetation growth boundary exhibited a more complex but more orderly trend. The vegetation growth boundary appears more chaotic than the shoreline; this is because plant recovery after land reclamation activities results in less breakpoints in the former area. The four indices we employed here have great potential utility for monitoring coastal wetland conservation and utilization in regions with intensive land reclamation. Furthermore, the combination of several indices can provide a more comprehensive and representative illustration of the state of ecology. Although we used shape entropy to study the Yangtze River Estuary, this index can also be applied in other coastal regions or landscapes.

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