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MARINE DEVELOPMENT

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Spatiotemporal evolution of coastal wetland resources in northern Rizhao under the influence of human activities

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Abstract

Coastal wetlands are a vital resource for the sustainable development of coastal areas. This paper presents a comprehensive monitoring of coastal wetland resources and their evolution in the northern region of Rizhao using multi-period remote sensing data and field investigations. The results show that as of the 2020s, wetland resources in northern Rizhao include subtidal wetlands, artificial wetlands, and intertidal wetlands, accounting for 38.5%, 34.2%, and 26.7% of the total wetland resources, respectively. Over the past 35 years, the evolution of wetlands has been divided into two stages according to the impact of human activities. Before 2000, the wetland area expanded rapidly due to beach aquaculture development. Subsequently, after 2000, the beach wetland area experienced a decline, whereas the landscape wetland area increased. The reason for the change in the wetland area in the later stage was the artificial change in wetland type and beach erosion. By 2020, coastal erosion gradually became the main factor driving the change in wetlands. Therefore, strategies and measures aimed at promoting natural beach growth should be implemented by regulating coastal engineering activities.

Keywords Northern Rizhao, Coastal wetland types, Distribution, Spatiotemporal evolution, Driving mechanisms

1 Introduction

The coastal wetland ecosystem, located at the edge of land and sea, is crucial to resisting storm surges, preventing coastal erosion, ensuring biodiversity, purifying coastal pollution, and other functions (Cheng et al., 2016). While discussions on coastal wetlands abound (Islam et al., 2017), a comprehensive scientific definition remains elusive. Drawing from the Convention on Wetlands and definitions in Europe and the United States, Lu defines coastal wetlands as regions with a land edge predominantly composed of 60% hygrophyte vegetation, expanding to a water edge 6 m below sea level. This definition includes all water-rich zones, natural or artificial, saltwater or freshwater, in river basins, excluding regions with water depths exceeding 2 m in the dry season, regardless of whether the water in the area is flowing or static intermittent or stagnant (Lu, 1996). Coastal wetlands, as unique ecosystems shaped by the dynamic interaction between water and land, boast various resources but are vulnerable to disturbance from human activities (Sun et al., 2011; Vitousek et al., 1997), particularly amidst rapid coastal economic development. The contradiction between wetland development and ecological balance preservation for economic interests

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is evident. For example, the intensity of human activities such as land reclamation, mariculture, coastal city expansion, and tourism development and construction in coastal wetland areas has continued to increase (Luo et al., 2022; Wang et al., 2018), leading to 50% of China's coastal wetland areas since the founding of the People's Republic of China according to statistics. This large-scale reduction and functional degradation of coastal wetlands have precipitated ecological and environmental challenges, including seawater intrusion, coastal erosion, biodiversity reduction, and water pollution (Islam et al., 2017; Rodríguez et al., 2017; Zhang et al., 2010), thereby impacting the lives and sustainable development of coastal communities. Following the 19th National Congress of the CPC, coastal economic development shifted toward a comprehensive and refined mode (Gu, 2023; Sun et al., 2015), necessitating renewed attention to coastal wetlands development and ecological restoration. Understanding the current status and evolution of existing coastal wetlands vis-à-vis human activities is important for measuring ecological coastlines. These endeavors not only support the sustainable economic development of coastal areas and inform decision-making processes but also hold significant practical importance for wetland restoration and protection (Cui et al., 2016; Adriana et al., 2018).

Satellite remote sensing is the main method used in coastal wetland research (Bortels et al., 2011; Sun et al., 2011). Extensive investigations employing multi-phase remote sensing data have elucidated coastal wetlands across regions such as the Bohai Sea, Jiangsu, and major estuaries south of Hangzhou Bay and large wetlands such as Qiantang River Hangzhou Bay, Jinjiang Estuary Quanzhou Bay, Pearl River Estuary estuary Bay, and Beibu Bay (Cai & Chen, 2016; Li et al., 2011; Yao et al., 2014), culminating in the establishment of China's coastal wetland classification system (Mou et al., 2015). These studies delve into the formation, development, and evolution of coastal wetlands under the influence of natural and human activities (Cahoon et al., 2006; Cui et al., 2018; Liu et al., 2018). However, the sand bars-lagoon coast in northern Rizhao, Shandong Province, presents a distinct landscape characterized by pristine beaches and natural wetlands. The coastline and coastal wetland distribution in this area have changed greatly due to aquaculture and other human factors in recent decades, yet data on wetlands in this area remain scant. This paper addresses this gap by employing satellite remote sensing and field survey methods to determine thematic element information of coastal wetlands in northern Rizhao, comparing conversion between natural and constructed wetlands, and analyzing spatiotemporal changes and driving mechanisms over the past 35 years.

2 Materials and methods

2.1 Study area

The study area lies along the Yellow Sea on the southern bank of the Shandong Peninsula (Fig. 1), stretching from the Baima River between Rizhao and Qingdao to the northern tip of Shijo Port in Rizhao, from north to south. It is bounded by Rizhao Beihai Road and Qingdao Road, with an average distance of 1.5 km from the coastline. The 6 m isobath was measured from the sea in December 2017. Geographically, the study area includes the coastal plain adjacent to the hilly area of eastern Shandong, which is characterized by well-developed water systems and short tributaries such as the Baima and Chao Rivers, which supply ample sediment to the region. The coastline predominantly extends in the NE-SW direction. The prevailing wave direction predominantly falls within the E-NE-NNE range, with normal wind waves originating from the north. Tidal patterns exhibit a normal semi-diurnal cycle, with the main tide direction oriented NE-SW. The confluence of waves and tidal currents engenders a coastal current flowing from north to south, facilitating sediment migration and ultimately producing a 22-km-long sandy coastline. Renowned as the Golden Coast due to its tourism potential, this area has emerged as an important folk tourism resort in Rizhao City over the past decade (Guo et al., 2009). Given its significance in regional tourism, understanding the current status of coastal wetlands in this area is of particular importance.

2.2 Data collection and processing

Google Earth (hereafter abbreviated as 'GE') is a freely accessible satellite imaging software launched by Google in June 2005. GE provides satellite images of various resolutions as fundamental data. Before 2005, the satellite images provided by GE boasted resolutions ranging from 8 to 15 m across the entire region, with post-2005 high-definition areas reaching resolutions of 0.6 to 1.0 m (Jin et al., 2009). The minimum patch size attainable in these images is 0.001 hm^2. The accuracy of GE's satellite images is sufficient for civilian investigation or research endeavors, including wetland status surveys. The 91 Satellite Map Assistant commercial software processed GE's historical images without displacement, ensuring precise alignment of images across different years, thus providing the analysis of wetland historical changes. For this paper, the 91 Satellite Map Assistant commercial software was used to download yearly images without displacement from 1984 to 2020. Wetlands were delineated using visual interpretation methods within the ArcGIS software. Field surveys and verification were conducted, including beach profile measurements and identification of wetland vegetation types, at locations such as the Baima Estuary, Chaohe Estuary, Rizhao National Forest Park, coastal

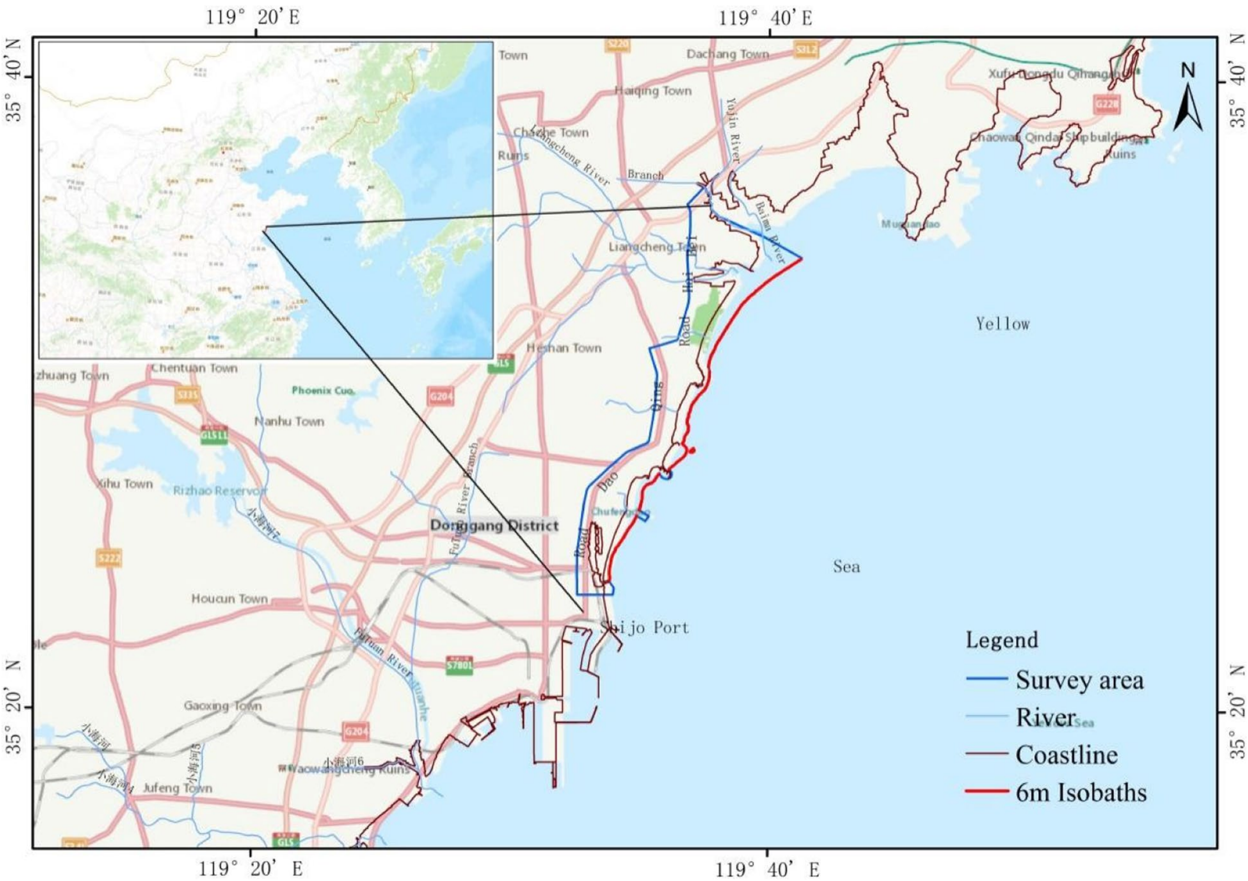

Fig. 1 Location of the study area (Blue box for the study area)

beaches in the resort area, and Wanpingkou Lagoon Park from October to December 2017, The − 6 m isobath at the lower boundary of the wetland was measured in December 2017. Combining field surveys with historical images, the area, types, distribution, and changes of coastal wetlands in northern Rizhao were analyzed.

3 Results

3.1 Types of coastal wetlands

Applying Lu's wetland classification system (Lu, 1996) in conjunction with the specific characteristics of the coastal area north of Rizhao City, the coastal wetlands study area is categorized into two groups: natural and artificial wetlands. Natural wetlands are further subdivided into three subcategories: supratidal, intertidal, and subtidal wetlands. All natural and artificial wetlands are further classified into nine types (Table 1).

3.2 Area and distribution of the coastal wetlands

Based on the 2020 GE image, the coastal area north of Rizhao City spans from the northern tip of Shijo Port to the eastern extent of Beihai Road and Qingdao Road, including the area up to the 6-m isobath. The total wetland area measures 3677.0 hm^2, comprising distinct categories as follows:

Supratidal wetlands cover an area of 20.43 hm^2, mainly located at river mouths with terrestrial vegetation unaffected by tidal fluctuations, accounting for 0.6% of the total wetland area.

Intertidal wetland extends over 981.53 hm^2 and includes rock beaches (e.g., Taigong and Taohua Islands), sandy beaches (all beaches in the northern region of Rizhao), the southern tidal beach of Baima Boundary River, the tidal beach of Liangcheng Estuary, and the connecting waters between Wanpingkou Lagoon Lake and the open sea. Boundary range from the super high tide line to the lowest low tide line, constituting 26.7% of the total wetland area and ranking as the second-largest wetland type in the study area.

Subtidal wetlands span 1417.22 hm^2, including areas from the lowest low tide line to 6 m isobaths, representing 38.5% of the total wetland area and emerging as the most prevalent wetland type in the study area.

Table 1 Classification system of the northern coastal wetlands in Rizhao City

Category	Subcategory	Type	Meaning description
Natural wetland	Supratidal wetland	River wetland	Rivers with average riverbed width ≥ 10 m and area > 10 hm2 and their floodplains
	Intertidal wetland	Rocky beach wetland	Between the low tide line and the high tide line, more than 75% of the substrate at the bottom is rock, and the vegetation coverage is less than 30%
		Beach wetland	The intertidal vegetation coverage is less than 30%, and the sediment is mainly sand and gravel
		Tidal flat wetland	The vegetation coverage is less than 30%, and more than 75% of the sediment is silty sand
		Lagoon wetland	The lagoon water area is formed by separating the wetland water body from the adjacent sea area by the coastal sand bar, sand mouth or offshore sand bar
	Subtidal wetland	Shallow water wetland	For the permanent water area with water depth ≤ 6 m at low tide, the vegetation coverage is less than 30%, including bays and straits
Artificial wetland		Landscape wetland	Artificial landscape water surfaces and recreational water surfaces built to beautify the urban environment
		Aquaculture pond wetland	Artificial water bodies used for the aquaculture of aquatic organisms such as fish, shrimp and crabs, including aquaculture ponds, intake and drainage channels, etc
		Salt wetland	Artificial water bodies used for salt production, including sedimentation tanks, evaporation tanks, crystallization tanks, intake and drainage channels, etc

Natural wetlands, totaling 2419.2 hm^2, constitute 65.8% of the total wetland area. The constructed wetlands include aquaculture ponds, salt marshes resulting from sea reclamation, and urban landscape water surface created through projects such as the Rizhao Olympic Water Park, amounting to 1257.8 hm^2 and accounting for 34.2% of the total wetland area. See Table 2 for the detailed statistics and Fig. 2 for wetland distribution.

4 Discussion

4.1 Evolution characteristics of coastal wetlands

The statistics on the characteristics of coastal wetlands in this article were conducted at five-year intervals, enabling an assessment of the statistical results in the wetland area since 1985, as shown in Table 3.

The wetland area change is shown in Fig. 3. According to the change in the artificial wetland area shown in Fig. 3, the evolution of the northern coastal wetland can be divided into two stages. The first stage spans from 1985 to 2000, during which the total wetland area gradually increased at an average growth rate of 6%, reaching a peak in 2000, with a decrease of 275.4 hm^2 in natural wetlands and an increase of 498.3 hm^2 in artificial wetlands. The growth rate of artificial wetlands outpaced that of natural wetlands during this period. The second stage covers from 2000 to 2020, during which the total wetland area experienced a continuous decrease at an average rate of 5.2%. The natural wetland area underwent minimal changes during this stage. The decrease in the total area is mainly attributed to the reduction of artificial wetlands.

To understand the changes in the area of the individual types of wetlands, Fig. 4 is plotted to depict the changes in the area of various wetland categories over time.

Table 2 Area of coastal wetlands in northern Rizhao City, 2020

Category	Type	Area (hm^2)	Percentage	
Supratidal wetland	River wetland	20.43	0.56%	0.6%
Intertidal wetland	Rocky beach wetland	119.06	3.24%	26.7%
	Beach wetland	565.63	15.38%	
	Tidal flat wetland	263.56	7.17%	
	Lagoon wetland	33.28	0.91%	
Subtidal wetland	Shallow water wetland	1417.22	38.54%	38.5%
Artificial wetland	Landscape wetland	218.59	5.94%	34.2%
	Aquaculture pond wetland	918.04	24.97%	
	Salt wetland	121.18	3.30%	
Total		3677.00	100%	

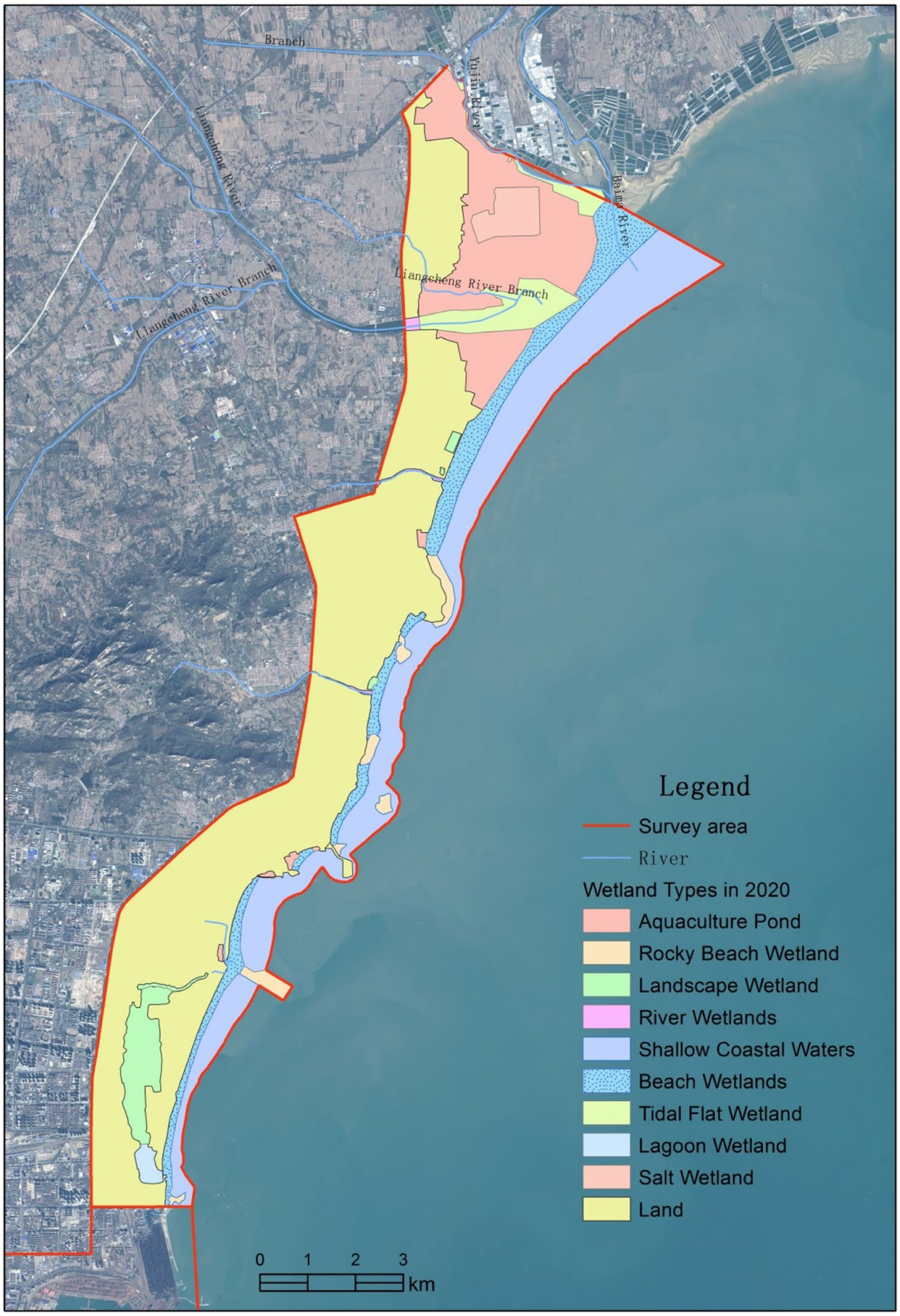

Fig. 2 Distribution of coastal wetlands in northern Rizhao City, 2000

From Fig. 4, it is evident that the changes in wetlands such as rivers, rocky beaches, tidal flats, shallow seas, and salt fields are minimal and relatively consistent, while significant changes occur in beach, landscape, and aquaculture pond categories. Their evolution exhibits regional and temporal differences.

The first stage of wetland evolution is mainly attributed to large-scale coastal reclamation in the northern region and the establishment of aquaculture ponds on land. Coastal land has been transformed into aquaculture ponds, peaking around the year 2000. Before 1985, the water area south of the Rizhao Liangcheng constituted a naturally formed lagoon wetland. However, between 1985 and 2000 (as shown in Figs. 5 and 2), the construction of aquaculture ponds and the disappearance of the lagoon led to a 74% increase in the aquaculture pond

Table 3 Area changes of coastal wetland types in Northern China 1985–2020 (Unit: hm^2)

Year Type	1985	1990	1995	2000	2005	2010	2015	2020
River wetland	19.8	27.9	13.1	8.9	11.6	6.7	6.7	20.4
Rocky beach wetland	86.5	85.3	85.3	82.1	78.7	78.7	78.7	119.1
Beach wetland	850.8	797.8	723.5	715.9	633.8	634.7	634.1	565.6
Tidal flat wetland	334.1	288.4	286.4	277.4	281.8	281.2	285.1	263.6
Lagoon wetland	36.8	0.0	0.0	0.0	34.8	34.8	34.8	33.3
Shallow water wetland	1376.1	1354.7	1353.2	1344.4	1340.4	1340.4	1340.4	1417.2
Landscape wetland	0.0	0.0	0.0	0.0	0.0	152.4	152.4	218.6
Aquaculture pond wetland	671.7	936.0	1059.0	1168.1	1086.0	863.1	848.5	918.0
Salt wetland	100.6	102.5	102.5	102.5	124.7	124.7	124.7	121.2
Total area	3476.4	3592.7	3623.1	3699.3	3591.8	3516.6	3505.4	3677.0

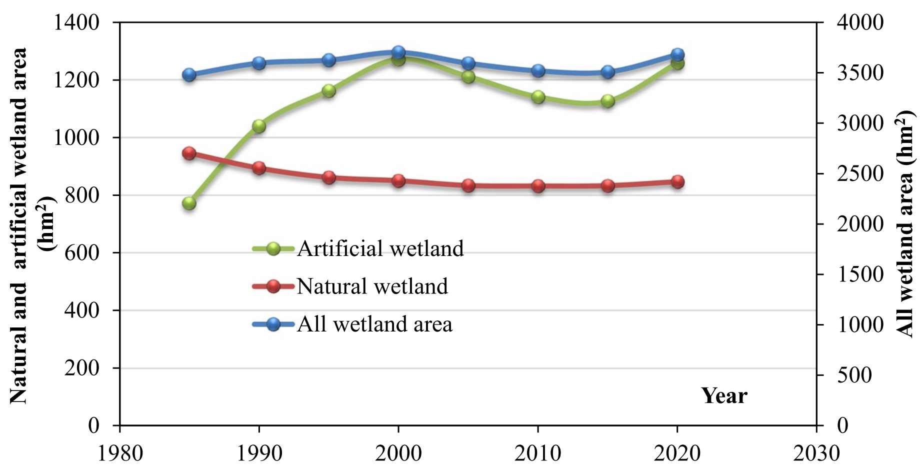

Fig. 3 Area change of coastal wetlands in northern Rizhao over the past 35 years

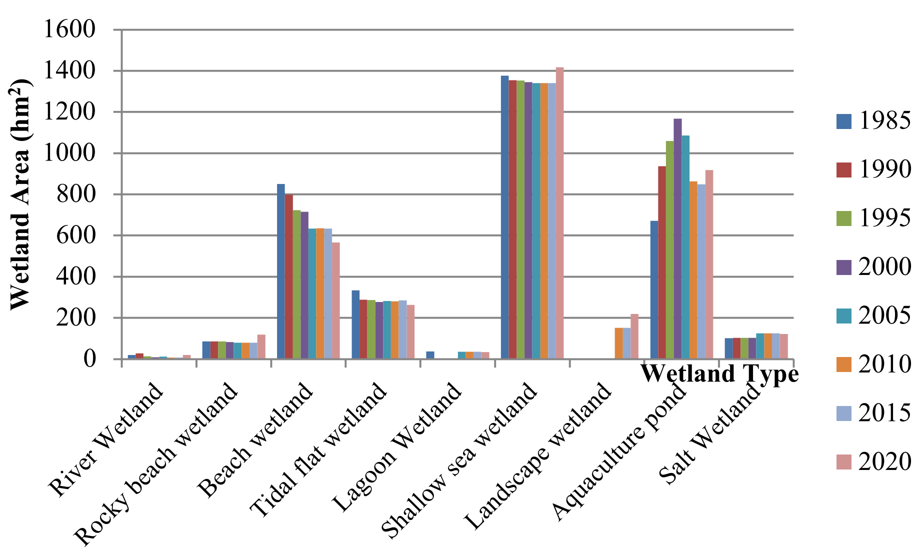

Fig. 4 Annual variation of landscape area of coastal wetlands in northern Rizhao

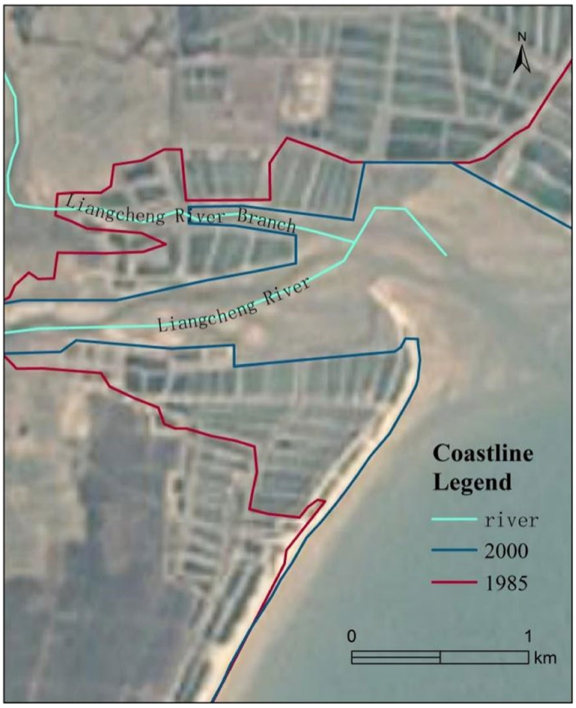

Fig. 5 Shoreline changes at the mouth of the Liangcheng River between 1985 and 2000

area. In September 1995, the establishment of the Rizhao Shanhaitian tourist resort in the north of Rizhao City prompted a shift in coastal development policies. Consequently, no new aquaculture ponds emerged in the north after 2000. However, the area of beach wetlands, resulting from pond construction near the sea, declined rapidly until 2000. The change in wetland area can be attributed to the transformation of natural and constructed wetlands and changes in location.

In the second stage of wetland evolution, a pattern of eastward development emerged in Rizhao City after 2000. Guided by the principles of the 'Two Mountains Theory', Rizhao City intensified efforts in ecological restoration and the creation of a livable environment in the eastern coastal wetlands. This includes modifying the characteristics of the aquaculture pond in Wanpingkou Lagoon since 2004. Some areas were filled in, while others were excavated to create recreational landscape water areas in conjunction with land infrastructure in the southern part of the wetland (Fig. 6a, b). Simultaneously, existing water bodies along the coastal land were expanded and refurbished. New landscape water bodies were constructed through the development of small islands and roads, resulting in a continuous expansion of landscape water bodies in the northern part of Rizhao and an accelerated beautification of the ecological environment. An

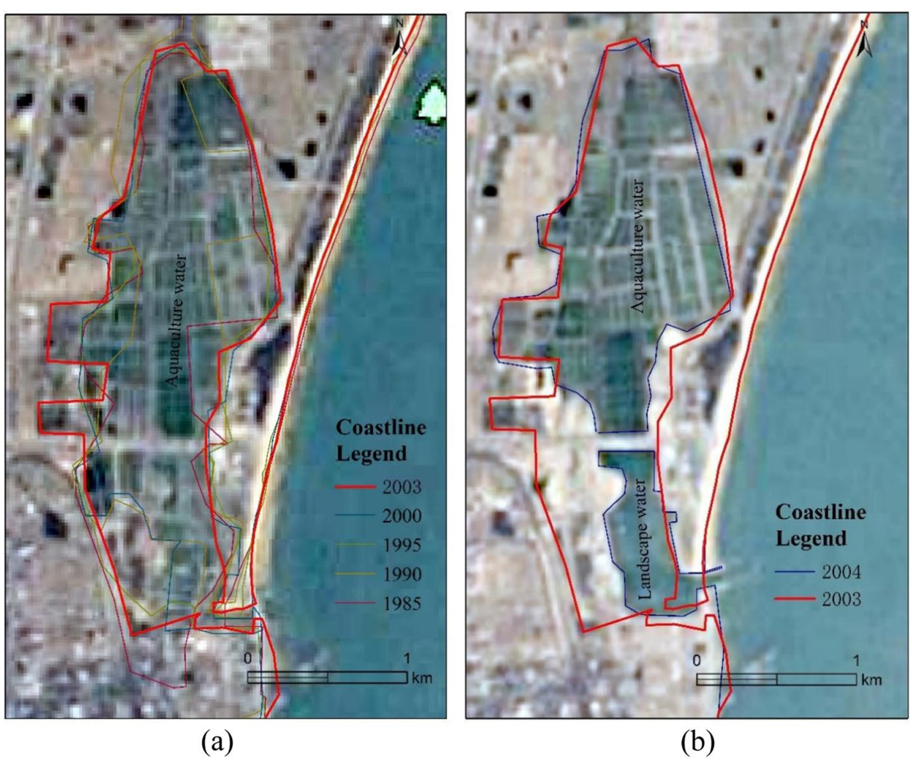

Fig. 6 Changes in the Lagoon Shoreline in Rizhao City. **a** from 1985 to 2003; **b** from 2003 to 2004

intriguing observation in the second stage is the increase in the area of rocky beaches and shallow sea wetlands, accompanied by a decrease in the beach area. By comparing with the evolution of the coastline, it was noted that some coastal sections have receded due to coastal erosion. The erosion of the sand layer covering the original rocky beach has facilitated a mutual transformation between the natural wetlands. This constitutes the fundamental reason for the minimal change in the natural wetland area during the second stage.

4.2 Driving mechanism of coastal wetland evolution

Factors influencing the evolution of coastal wetlands in the northern part of Rizhao include both human-induced and natural factors, as elucidated in the preceding analysis. The change in beach wetland areas due to coastline erosion and sedimentation exemplifies natural processes, whereas changes in beach and shallow sea wetland areas resulting from activities such as mudflat pool reclamation, coastal reclamation and expansion, and artificial pool excavation reflect human influences. Statistics regarding changes in beach wetland areas attributable to natural and artificial factors were conducted in two stages, as presented in Table 4 and Fig. 7.

It is evident from Table 4 and Fig. 7 that human activities have significantly influenced changes in beach wetland areas. During the period from 1985 to 2000, artificial wetland areas accounted for 89.3% of the total change area, with natural factors contributing only 10.7% (Fig. 7a). This is consistent with the extensive reclamation of ponds during the initial stage. In the subsequent stage, changes in wetland areas attributed to natural conditions accounted for 71.2%, whereas those due to human activities such as sea reclamation and pond excavation constituted 28.8% (Fig. 7b). This indicates a notable decrease in human intervention in coastal wetlands, with natural conditions emerging as the main factor. As development policies were adjusted and Rizhao's coastal protective development strategy was upgraded, coastal wetland types underwent mutual transformation. Enclosed sea ponds were transformed into leisure and scenic landscape wetlands. With intensified human activities, the role of nature has also become increasingly prominent. Notably, 70.2% of the change area in beach wetlands was attributed to coastal erosion. In the first

Table 4 Change in beach wetland area in northern Rizhao (Unit: hm^2)

Reason for change	Change state	1985–2000	Percentage	2000–2020	Percentage
Natural	Erosion regression	36.09	10.4%	54.73	67.4%
	Sedimentation	1.14	0.3%	3.10	3.8%
Artificial	Reduce	0.00	0.0%	16.63	20.5%
	Increase	309.24	89.3%	6.70	8.3%

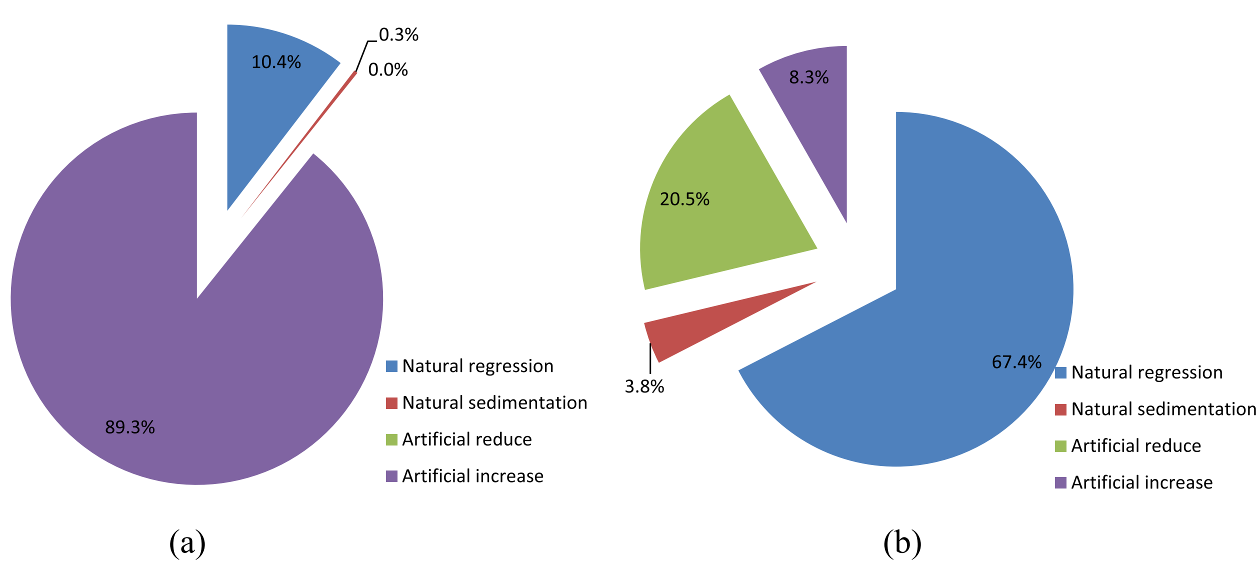

Fig. 7 The proportion of driving factors for coastal wetland evolution. **a** 1985 to 2000; **b** 2000 to 2020

stage, human activities such as pond construction near the sea were the main driving force behind the evolution of Rizhao's coastal wetlands, with natural factors playing a minor role. However, in the second stage, natural factors predominated in the evolution of beach wetlands. The late stages of coastal wetland evolution in northern Rizhao were predominantly influenced by natural factors. Hence, the subsequent focus should be on researching methods and measures to promote beach growth under natural conditions (Liu et al., 2021) and fostering beach development by regulating coastal engineering activities. Under the guidance of the 'Two Mountains Theory' policy, landscape wetlands in the north of Rizhao are progressively expanding, further enhancing the ecological environment.

This investigation has elucidated the spatial–temporal variation patterns and driving mechanism governing the distribution status of wetland resources, types, areas, and locations in Rizhao City, thereby furnishing strong data support for the monitoring and management of the Rizhao coastal zone in subsequent endeavors.

5 Conclusions

(1) In 2020, the wetland types in northern Rizhao were classified into nine categories, involving a total area of 3677.0 hm^2. Subtidal wetlands constituted the most prevalent type in the study area, covering 1417.22 hm^2 (38.5% of the total), followed by artificial wetlands with an area of 1257.8 hm^2 (34.2%) and intertidal wetlands spanning 981.53 hm^2 (26.7%). The remaining categories exhibited a lesser distribution.

(2) The evolution of coastal wetlands in northern Rizhao can be divided into two stages, with 2000 serving as the midpoint. The first stage witnessed a rapid increase in the area of aquaculture pond wetlands alongside a decreased beach wetland area. Conversely, in the second stage, the beach wetland area continued to decline, whereas the landscape wetland area experienced growth.

(3) Human activities constituted the main driving force behind the evolution of the Rizhao coastal wetland during the initial stage. In the subsequent state, the evolution of coastal wetland types was ensured by the combined influence of human activities and natural processes, with coastal erosion gradually emerging as the main driving factor of wetland changes. The future task entails conducting research on methods and measures to promote beach growth under natural conditions and promoting beach development through the regulation of coastal engineering activities.

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All author(s) read and approved the final manuscript.

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Declarations

Competing interests
The author declare that they have no competing interests.

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