Journal of
Marine Science and Engineering

Article

The Rapidly Evolving Fudu Estuary Sandbar Lagoon Landform on the East Coast of the Bohai Sea: Recent Changes and Mechanism

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Abstract: The Fudu Estuary Sandbar Lagoon is one of the most representative sandbar-lagoon landforms in China, and has undergone drastic evolution in recent years, accompanied by increased coastal engineering activities. The evolution process and its control factors are studied through remote sensing interpretation and coastal sediment transport calculations. During 2010–2021, the sandbar quickly extended at an average speed of 49.5 m/a, but the annual growth has shown a decreasing trend in both area and width, and the shoreline has retreated by 25–45 m. The recent changes are the result of the combined action of natural conditions and human activities. Coastal sediment transport from west to east under the action of W-oriented waves is the natural cause of extension. An estuary dam and artificial island block the sediment transport path, and the material for the new growth of the sandbar comes from the erosion of its west side, which has directly caused the retreat and narrowing of the sandbar. The reduction in sediments from the river further aggravates the shrinkage. It is predicted that the sandbar will continue its eastward extension to connect with the coast in about 2–3 years. The erosion status is unlikely to change before the sediment supply is restored. Measures such as dismantling the estuary dam are recommended.

Keywords: Bohai Sea; Fudu Estuary; sandbar-lagoon; human activity; evolution; remote sensing image

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Citation: Zhang, L.; Yan, J.; Zhao, B.; Lin, X.; Wang, P.; Zhang, C.; Yu, Y.; Zhang, P. The Rapidly Evolving Fudu Estuary Sandbar Lagoon Landform on the East Coast of the Bohai Sea: Recent Changes and Mechanism. *J. Mar. Sci. Eng.* **2021**, *9*, 1350. https://doi.org/10.3390/jmse9121350

Academic Editors: Giorgio Anfuso and João Miguel Dias

Received: 23 October 2021
Accepted: 23 November 2021
Published: 30 November 2021

1. Introduction

The sandbar-lagoon is a typical coastal accumulation landform body composed of three geomorphic units: sandbar, lagoon and tidal inlet, and is widely found in estuaries and other coastal areas with abundant sediment sources. The sandbar-lagoon coast has a typical sandy coastal ecosystem, offers unique landscape and scientific research value, and plays an important role in coastal protection, ecological balance and coastal landscape beautification. Lagoon coasts are widely distributed throughout the world [1]. In China, they are mainly found in Guangxi, Guangdong, Zhejiang, Liaoning, the Shandong Peninsula and North of Bohai Bay [2]. Though not large, coastal lagoons in China are numerous in number and type [3]. High-intensity coastal development in recent decades has subjected China's lagoon coasts to varying degrees of damage [4]. Jingtang Lagoon [5] and Qilihai Lagoon [6] on the west coast of Liaodong Bay, and Chaoyang Port Lagoon, Moye Island Lagoon and Linjialiu Lagoon [7] in the Shandong Peninsula have disappeared. The protection of lagoon coasts has attracted nationwide as well as worldwide attention [8].

Characterized by continuous monitoring and simple data acquisition, remote sensing imaging is a mature technology for quantitative analysis of sandbar shoreline changes and morphological characteristics. Based on the analysis of remote sensing characteristics of various coastal lagoons, a remote sensing classification method in terms of geomorphological origin and evolution stage of coastal lagoons was proposed [9]. Multi-temporal remote sensing image interpretation is widely used in long-term evolution research [4,10]. Through the Kauth–Thomas transformation, the humidity parameters are extracted from remote sensing images to obtain the historical high tide line, and the evolution of the Xincun Lagoon and Li'an Lagoon in Hainan Province of China are analyzed [11]. Based on SPOT images of the southwest coast of France, Lafon et al. used parameterized reflectivity to extract the shape of the crescent sandbar and analyzed the migration status [12]. Athanasiou et al. used remote sensing images to manually extract the sandbar of South Korea's Anmok Beach and verified them by in-situ measurements, found that the sandbar had migrated approximately several hundred meters in 27 years [13]. The evolution of the sandbar-lagoon is closely related to the change of the dynamic environment. The strong wave activity leads to large sediment mobility and erosion or deposition processes and affects the coastline shaping of Colpan Barrier and Lagoon [14]. The sediment flux in the barrier estuary of Chincoteague Bay in the United States is modulated by strong winds, and storm events play an important role in the estuary fluid dynamics and overall sediment budget [15]. The relationship between geomorphic evolution, natural conditions and human activities has become a focus under the social concern and urgent need to protect and restore lagoon coast damage. For example, the decrease in the amount of sediment entering the sea caused by the construction of reservoirs in the upper and middle reaches of the Luan River, and the construction of reclamation are considered to be the main reason for the shrinkage of the lagoon-sandbar in the Luan River Delta [10]. Sandbar-lagoon coastal systems are highly sensitive to changes in external conditions (sediment input, hydrodynamic force, and nutrient balance, etc.) [16]. The coastal erosion of the Shandong Peninsula is thought to be related to reduced sediments supply from rivers [17]. Wave dynamic conditions are believed to be the main dynamic factor controlling the evolution of the lagoon coast, as they dominate the transport of coastal sediments [14,18]. Human activities such as tidal flat reclamation, coastal sand mining and aquaculture have caused significant changes in environmental conditions, which significantly impact the evolution of the lagoon coast [19].

The Fudu Estuary Sandbar Lagoon (FESL, 40°07′ N, 121°57′ E) is located on the east coast of Bohai Sea in China (Figure 1), developed from the rich sediment supply of the Fudu River. It is one of the most typical sandbar-lagoon geomorphic systems in China, with large scale and relatively complete preservation. Unlike most of the relatively stable coastal lagoons in the world, the FESL has been undergoing drastic evolution in recent years. The rapid extension and significant retreat of the sandbar are rare in the world. This unique case is of great value for understanding the dynamic mechanism of the evolution of the FESL. However, there is essentially no research on the FESL, except our several previous studies [20–22]. Hence, it is imperative to figure out the processes and mechanisms of its geomorphological evolution, and to take measures to protect and restore it under scientific guidance.

Based on high-resolution remote sensing images, this paper studied the geomorphological evolution of the FESL for the first time, quantified the changes in geomorphic parameters of the FESL in the past ten years, clarified the response of coastal engineering to geomorphic parameters, and revealed the reasons for the rapid extension and significant retreat of sandbar combined with the calculation of coastal sediment transport. In addition, the evolution trend of the FESL was predicted, and suggestions were put forward to ease the retreat of the sandbar. This paper can provide a scientific reference for the protection and restoration of the FESL.

Figure 1. Geographical Location and Overview of the Fudu Estuary Sandbar Lagoon (FESL). Remote sensing images are obtained from ESRI with a spatial resolution of 2.39 m. Photos a, b, and c were taken in June 2021.

2. Materials and Methods

2.1. Study Area

The FESL is located at the estuary of Fudu River on the east coast of the Bohai Sea. Formerly an estuary type, it consists of an estuary on the inside, a sandbar on the outside, and a two-way tidal inlet between the two. Due to extensive coastal development, the sandbar on the south of the estuary has become the present-day coast (Figure 1). The remaining main part of the FESL is situated north of the estuary and is about 2.4 km long. The FESL has changed from an estuary type into a sandpit type and undergoes significant changes every year (Figure 2). The Fudu River has a basin of 466 km^2 and is the only river that flows into the surrounding waters. Fudu River has large discharge from July to September every year, and the average suspended sediment transported annually is about 11×10^4 t. On the north of Fudu Estuary is Baisha Bay, which has a relatively flat overall seabed landform. The sediments on the sandbar are medium and fine sand with average particle diameters of φ2–φ3 (expressed in the Udden–Wentworth Grade Scale); the sediments in the lagoon are mainly composed of silt and clay, with average diameters of φ4–φ6 [21].

The study area is affected by monsoons. Northerly and northeasterly winds prevail in winter; southerly winds prevail in summer; and southwesterly and southerly winds prevail in spring and autumn. The study area features an irregular semi-diurnal tide, with an average tidal range of 2.46 m. The tidal currents in the study area are reciprocal; the current direction of flood tide is NNE, and of ebb tide is SSW, and the current velocity of the former is greater than that of the latter. The waves in the study area are mainly composed of wind waves, with a height that varies from 0.2 m to 0.6 m. The dominated wave direction is SW or WSW, and the strongest wave direction is N or NNE.

Since the 1990s, massive coastal zone development activities have been carried out in the Fudu Estuary. Aquaculture was initially conducted within the lagoon by means of enclosed dikes. Around 2011, a fishing port was built to meet the berthing needs of fishing boats. The lagoon was divided into two parts, as the north bank of the river was extended to the sea and connected with the sandbar. The lagoon in the south of the estuary has been used for mariculture and reclamation, and the sandbar has been connected to the land to become the present-day coast. The lagoon in the north of the estuary has become a semi-closed lagoon with a single channel. An estuary dam, artificial island and reclamation area have been successively constructed in the north of the estuary since 2010 [22].

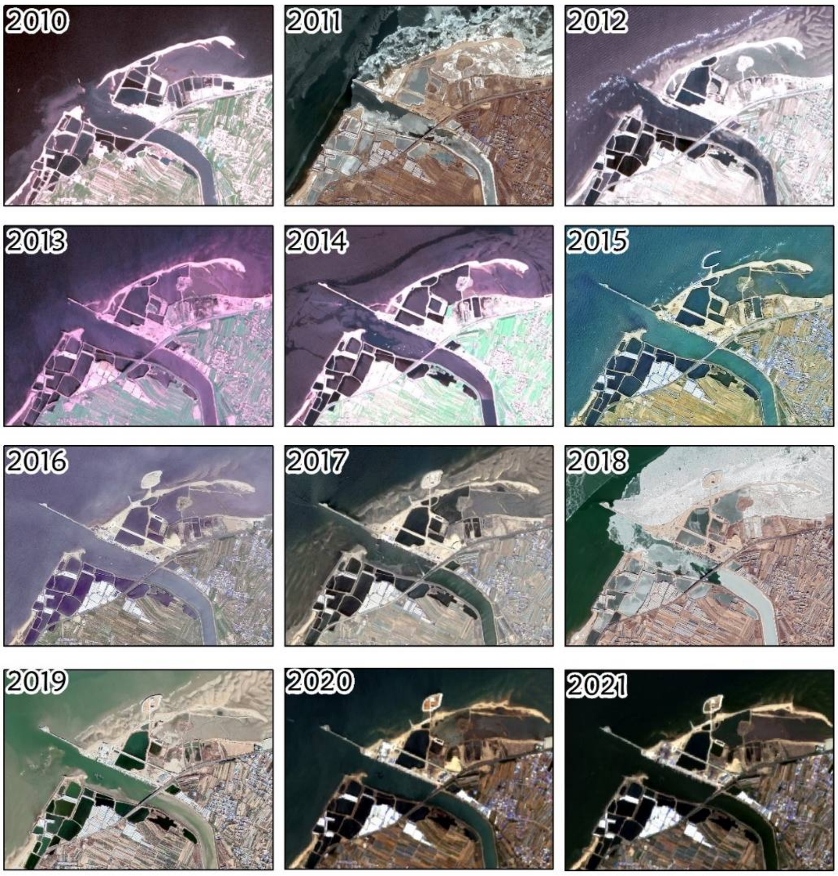

Figure 2. High Resolution Remote Sensing Images of the FESL from 2010 to 2021.

2.2. Remote Sensing Images

High-resolution remote sensing images of the study area have been collected since 2010 (Figure 2). The images from 2010 to 2019 were captured by SPOT, ZY and GF satellites, with a spatial resolution of 1.5–2.5 m. The images from 2020 to 2021 were captured by the Sentinel-2 satellites, with a spatial resolution of 10.0 m. Detailed information on each image is shown in Table 1.

Table 1. Time, source and resolution of high-resolution remote sensing images.

Year	Month	Satellite	Resolution/m
2010	June	SPOT	2.50
2011	March	SPOT	2.50
2012	April	ZY	2.36
2013	June	ZY	2.36
2014	August	ZY	2.36
2015	April	GF	1.50
2016	May	ZY	2.36
2017	April	GF	1.50
2018	January	SPOT	2.50
2019	July	SPOT	2.50
2020	May	Sentinel-2	10.0
2021	May	Sentinel-2	10.0

2.3. Interpretation Methods

Temporal and spatial variations in the characteristic parameters of geomorphic units were interpreted visually. The precision of visual interpretation is 1 pixel. Since the sandbar migrates dozens of meters a year, the resolution meets the needs of interpretation. The interpreted characteristic parameters include head position, annual new growth area and longitudinal migration of the sandbar. The interpretation methods of the respective parameters are as follows and are shown in Figure 3.

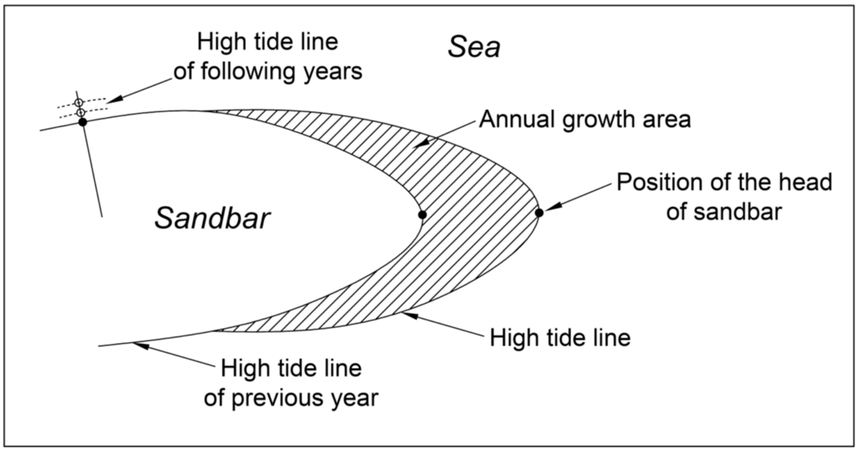

Figure 3. Schematic diagram of determining method of geomorphic parameters.

1. Outline of the sandbar. Draw outline of the sandbar based on the high tide traces. Affected by the difference in water content, the sandbar above the high tide line has high reflectivity due to dryness, and the image appears bright white. Therefore, the outline of the sandbar of each year can be obtained. The fluctuation of the high tide line on different dates and the slope of the sandbar will affect the interpretation results. However, field investigation found that the slope of the sandbar is large (the inclination angle is about 25–30°), and the error of the outline position caused by fluctuation of the high tide line is about 2–3 m. The error is only about 5% of the annual extension length of the sandbar (50 m on average) and has a limited impact on the results.
2. Position of the head of the sandbar. Draw the most curved point on the outline of the head of the sandbar. Therefore, the annual head position of the sandbar can be obtained.
3. Annual growth area of the sandbar. Draw the closed area formed between the outline of the sandbar in a certain year and the previous year. Therefore, the annual growth area of the sandbar can be obtained.
4. Longitudinal migration of the sandbar. Draw a section perpendicular to the outline of the sandbar at the selected position, and obtain the intersection point of the section with the outline. Taking the intersection in 2010 as the origin point, the distance between the origin point and the intersection point of each year is counted successively (a positive value for migration to the seaside and a negative value for migration to the land side).

2.4. Calculation Method of Coastal Sand Transport

The wave energy flux method is commonly used to calculate coastal sediment transport rate. The CERC [23] method of US Army Coastal Engineering Research Center, proposed on the basis of previous researchers [24], is the one most widely used. The wave energy flow method connects the sediment transport rate (I_l) and the coastal component of the wave energy flow (P_l). The calculation equation is as follows:

$$P_l = (Ecn)_b cos\alpha_b sin\alpha_b \quad (1)$$

$$I_l = K\, P_l \quad (2)$$

The conversion relationship between the volumetric coastal sediment transport rate (Q_l) and the weight sediment transport rate (I_l) is:

$$I_l = (\rho_s - \rho) g (1 - \varepsilon) Q_l \quad (3)$$

where, ρ_s and ρ are the density of sediment and water, g is the acceleration of gravity, and ε is the porosity of the sediment.

Komar and Inman proposed K = 0.77 based on a large number of experiments. Hu and Zheng [25] used shallow water waves to derive the calculation formula of Q_l, taking ε = 0.4, ρ_s = 2.650 kg m^{-3}, ρ = 1.025 kg m^{-3}, g = 9.80 kg m s^{-2}:

$$Q_l = 0.05059\, H_b^2 C_b sin2\alpha_b \quad (4)$$

where:

H_b is the wave breaking wave height, can be calculated according to the empirical formula proposed by Munk [26]. The calculation equations between L_0 (average wave length), H_0 (average wave height), T (average wave period), and H_b (breaking wave depth) are as follows:

$$\frac{H_b}{L_0} = \frac{1}{3.3(H_0/L_0)^{1/3}} \quad (5)$$

$$L_0 = \frac{gT^2}{2\pi} \quad (6)$$

$$\frac{H_b}{h_b} = 0.78 \quad (7)$$

C_b is the wave speed at the wave breaking point, can be calculated by the following calculation equation:

$$C_b = \sqrt{gh_b} \quad (8)$$

α_b is the wave direction angle at the wave breaking point. As the water depth contour is approximately parallel to the shoreline, the wave breaking conditions are approximately the same along the shore. According to Snell's law, α_b can be calculated by α_0 (angle between the wave direction and the normal direction of the coast) and T (average wave period):

$$\alpha_b = arcsin(C_b/C_0\, sin\alpha_0) \quad (9)$$

$$C_0 = gT/2\pi \quad (10)$$

3. Results

3.1. Changes in Head Position

The head of the sandbar has moved dramatically in recent years. The remote sensing images were interpreted to obtain the change in head position from 2010 to 2021 (Figure 4A). The sandbar is rapidly extending toward the shore. Over the past 11 years, it has grown eastward by about 544 m at an average rate of 49.5 m/a (Figure 5A). Since the image of 2018 was taken in January, the extension length for 2018 is relatively small, while for 2019 is relatively large. Overall, the extension rate was relatively stable between years.

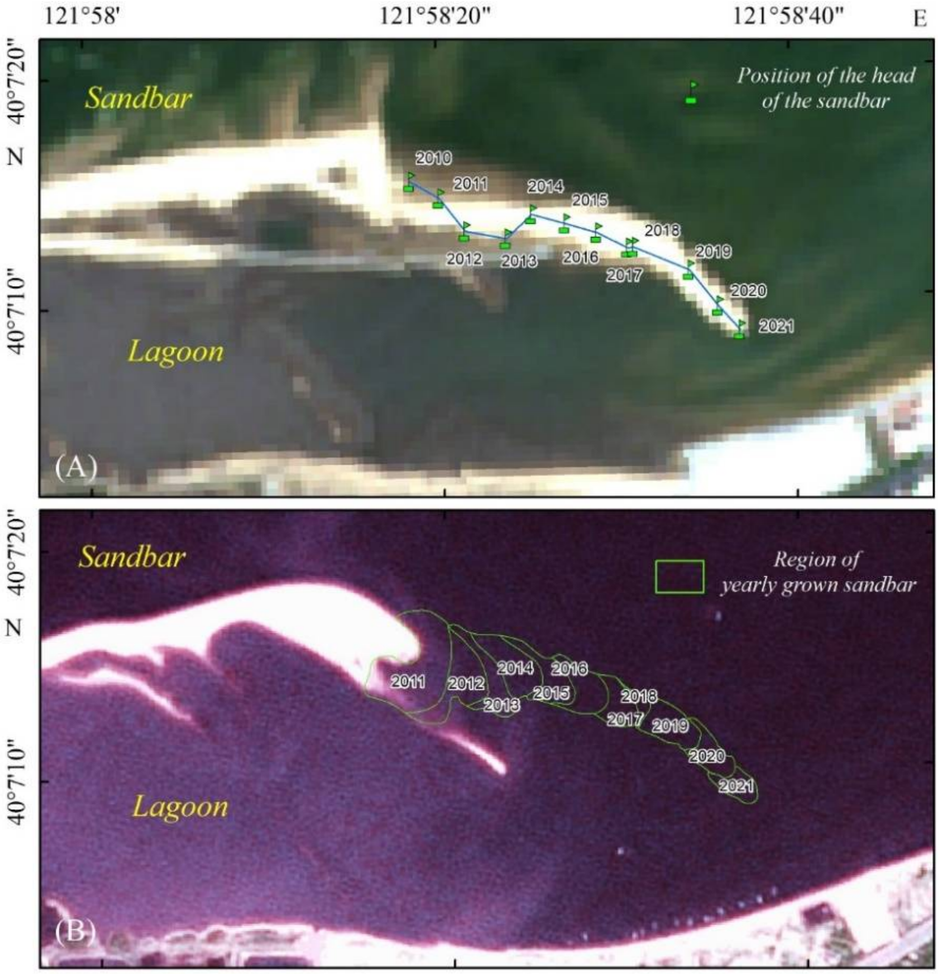

Figure 4. Lateral Evolution of the FESL. (**A**) Head position of the sandbar, base map is the remote sensing image in 2021; (**B**) Yearly growth region of the sandbar, base map is the remote sensing image in 2010.

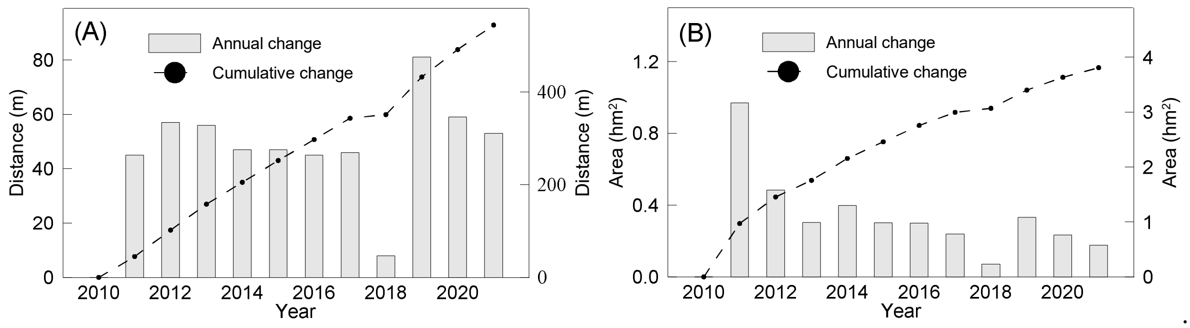

Figure 5. Annual and cumulative change of head position (**A**) and growth area (**B**) of the FESL taking 2010 as a reference.

3.2. Changes in Growth

As the sandbar has extended, its area has continuously increased. The remote sensing images were interpreted to obtain the change in annual new growth area from 2010 to 2021 (Figure 4B). In 2011, the new growth area amounted to about 1.0 hectares, and in 2020, it was less than 0.2 hectares (Figure 5B). Thus, although the area of sandbar is still increasing, its new growth area has a decreasing trend (-0.05 hm^2/a, $R^2 = 0.52$).

3.3. Longitudinal Offset

Four sections were selected to interpret the longitudinal offset of the sandbar. The positions of the sections are shown in Figure 1, and the interpretation result is shown in Figure 6. Section D1 had been extending to the sea before 2012, but it has slowly retreated by about 25 m since then. A new round of retreat has taken place at the D1 section, starting in 2016. Section D1 is located to the east of the estuary dam and the sediments are mainly composed of gravel and lack fine-grained components. Section D2 advanced slowly before 2012, retreated slowly after 2012, and quickly advanced about 25 m toward the sea after 2015. Section D2 is located on the southeast side of the artificial island, and a tombolo is developing. Section D2 is located in the wave shadow area of the artificial island and is the only section that is still advancing rapidly. Section D3 has receded rapidly by about 40 m since 2010 and eroded back to the gravel embankment in 2016. Section D4 quickly retreated about 25 m from 2011 to 2013, and then stabilized. Section D4 has undergone a second round of retreat (about 20 m) after 2015 and stabilized after 2018.

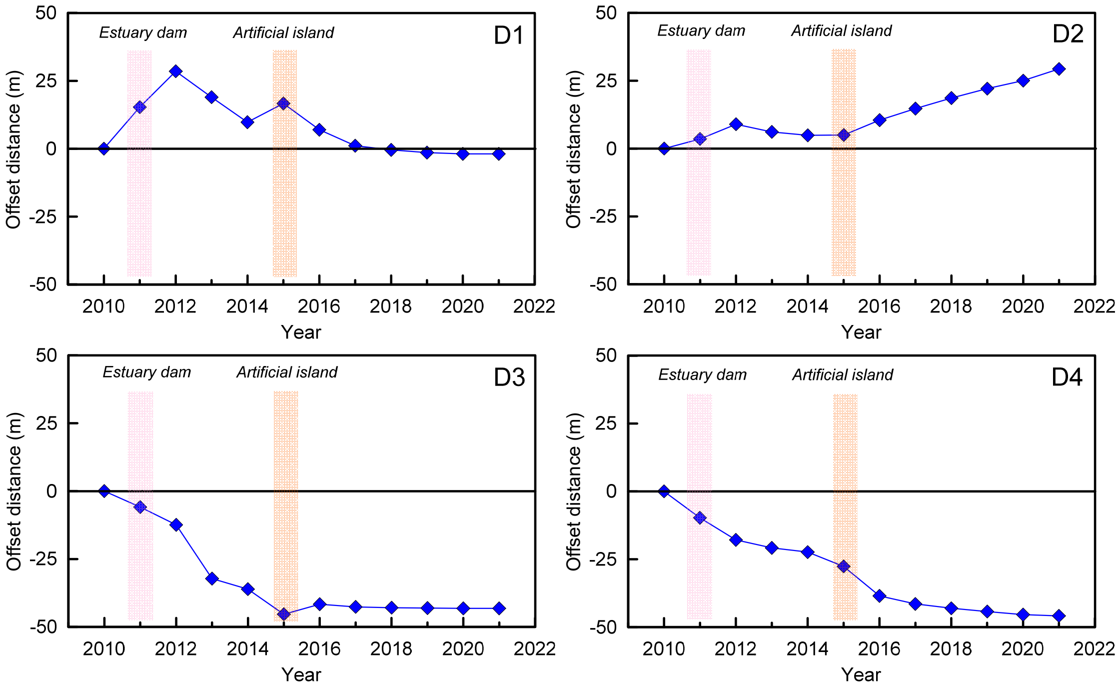

Figure 6. Longitudinal offset of the FESL at four sections. See Figure 1 for the section positions. Pink bands represent the construction of the estuary dam, and brown bands represent the construction of the artificial island. Positive values indicate migration toward the sea, and negative values indicate migration toward the land.

3.4. Coastal Construction Activities

Based on the remote sensing images, the main coastal development activities and construction sequence around the FESL were identified (Table 2). Enclosed sea areas for mariculture were the main form of development before 2010. A dam was built on the north bank of the Fudu Estuary in 2011 and expanded to 600 m long in 2017, and the lagoon was reclaimed to land. In 2015, an artificial island was built on the outer side of the sandbar. In 2016, the operator of the beach built a short jetty near the D1 section in order to prevent the loss of sand. In 2019, a shipyard was built on the north side of the estuary, and part of the coast was reinforced as a seawall.

Table 2. Coastal construction activities around the FESL.

No.	Artificial Structure	Position	Build Year
1	Enclosed sea area for mariculture	In lagoon	Before 2010
2	Estuary dam	North bank of Fudu Estuary	2011–2017
3	Reclamation	In lagoon	In 2011
4	Artificial island	Outer side of the sandbar	In 2015
5	Short jetty	Near the D1 section	In 2016
6	Shipyard and seawall	North side of the estuary	In 2019

4. Discussion

4.1. Factors Controlling the Extension of the Sandbar

In the nearshore area, the sediments disturbed by wave breaking are transported under the action of wave-generated coastal current, which is called coastal sediment transport. On sandy coasts, coastal sediment transport mainly occurs within the surf zone. Coastal sediment transport is considered to be a decisive factor affecting the long-term evolution of sandy coasts [27]. For the study area, since the sea area near the sandbar dries out at low tide, the sediment along the sandbar is transported when the sea area near the sandbar is submerged by sea water. In order to find out the status of sediment transport in the study area, the CERC method was applied. The dominated wave direction of the sea area outside the Fudu Estuary is SW or WSW. Due to the coastline direction and topographic shielding, only waves with a direction between WSW and NNW can act on the sandbar-lagoon area. Six sections were selected (see Figure 7 for their positions); the sediment transport rate along the coast from each wave direction was calculated respectively according to the wave observation data (Figure 7), and the total sediment transport rate (TSTR) was calculated as the sum of the sediment transport rates in each direction. The results (Table 3 and Figure 7) reveal that sediment migrates from west to east along the coast; the closer to the east of the sandbar, the greater the TSTR. By comparison, the TSTR of sections P1, P2 and P3 is similar, while that of sections P4, P5 and P6 significantly and progressively increases, which is consistent with the rapid eastern movement of the head of the sandbar found by remote sensing. Therefore, the primarily W-oriented wave condition is the hydrodynamic basis of the continuous eastward extension of the sandbar.

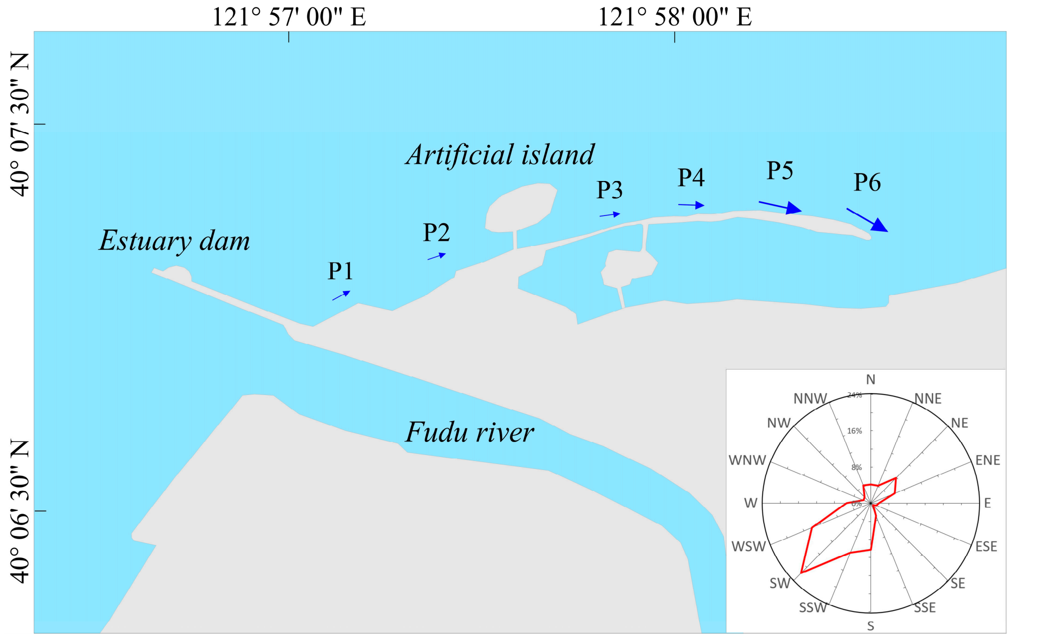

Figure 7. Coastal sediment transport along the sandbar under wave action.

Table 3. Coastal sediment transport rate of sections in FESL (unit: 10^4 m^3/a).

Wave direction	WSW	W	WNW	NW	NNW	Total sediment transport rate	Net sediment transport rate
Frequency/%	14	5	2	2	4		
H_0/m	0.11	0.21	0.37	0.31	0.51		
T/s	2.50	2.70	2.95	2.90	3.40		
$\alpha_0/^\circ$	82.5	60.0	37.5	15.0	−7.5		
P1	+0.59	+0.73	+0.70	+0.21	−0.66	+1.57	NA
P2	+0.59	+0.73	+0.68	+0.19	−0.74	+1.45	−0.12
P3	+0.60	+0.74	+0.72	+0.22	−0.57	+1.71	+0.26
P4	NA	+0.80	+0.86	+0.35	+0.31	+2.32	+0.61
P5	NA	+0.85	+1.07	+0.57	+2.01	+4.50	+2.18
P6	NA	NA	NA	+0.78	+4.19	+4.97	+0.47

Note: "NA" means not available; "+" means eastward; "−" means westward.

4.2. Factors Controlling the Retreat of the Sandbar

Although the sandbar is rapidly extending eastward, its annual new growth area is falling. Its new growth area in 2020 was only 20% of that in 2011. The width of the head is also gradually narrowing from about 110 m in 2010 to about 70 m in 2015, and less than 40 m in 2020. Meanwhile, the shoreline is receding to varying degrees.

The difference in TSTR between two adjacent sections (Figure 7 and Table 3) is the net sediment transport rate (NSTR), which represents the inflow and outflow of sediments within a segment and can indicate siltation or erosion trends within the segments between sections. The absolute value of the NSTRs of sections P2 and P3 is small, thus no erosion trend is evident. Section P5 has the greatest NSTR, followed by section P4, which indicates a strong erosion trend in the coastal segment between section P3 and P5. However, the NSTR of section P6 is far less than that of section P5, indicating that the erosion trend of the coastal segment between sections P5 and P6 is becoming weaker. Without considering coastal structures, the coastal segment between section P4 and P5 (located in the same area as section D4 in Figure 1 from remote monitoring) has the topographic conditions for strong net sediment loss and may be the main supply area of sediments needed for extension and growth of the sandbar. In short, the specific topography and wave conditions have naturally led to a sudden increase in the net sediment transport rate in the middle sandbar, which is also prone to be eroded.

Sediment discharge from Fudu River is the main source of the study area and is transported in a northeasterly direction under the force of the wave-generated coastal current. However, the estuary dam and artificial island block the coastal transport path of the sediments, as they extend across the surf zone. Built in 2011, the estuary dam extends 600 m into the sea. The longitudinal offset results from interpretation of remote sensing data (Figure 6) show that sections D1, D3 and D4 have undergone rapid retreat (2–4 m/a) since 2012. Obviously, after the construction of the estuary dam, the sandbar was eroded to varying degrees. Built in 2015, the artificial island stretches about 300 m to the sea. In 2014, sections D1 and D4 showed signs of equilibrium, but the retreat has intensified since 2015. Section D3 has eroded to the gravel embankment and receded no more. Section D2 is located in the wave shadow area of the artificial island due to W-oriented waves and has been rapidly silted into the sea since 2015. Section D2 is also the only section that is still advancing rapidly. This shows that the sections quickly responded to the construction of the estuary dam and stabilized within 3 years, and the second round of response process appeared after the construction of the artificial island. The above analysis indicates that the geomorphic characteristics of the sandbar have responded significantly to the coastal construction and are highly sensitive to changes in the coastal environment. With the coastal sediment transport path blocked, the east side will have insufficient supply of sediments, and the new grown sandbar will mainly gain material from erosion of the original sandbar, which will inevitably be accompanied by retreat and narrowing.

Therefore, the estuary dam and artificial island blocking coastal sediment transport are the dynamic factors causing shrinkage of the sandbar.

The shrinkage is also related to the decrease in river sediment input, which is considered to have played an important role in the erosional retreat of the east coast of Liaodong Bay [28]. The river sediment input is influenced by natural and human factors such as precipitation, runoff, soil and water conservation and river sand mining. In recent years, the climate in eastern Liaoning has been dry, and excessive exploitation of groundwater has led to a decrease in surface runoff [29]. Seawater intrusion has been found in the Fudu Estuary [30]. Afforestation and other greening activities will increase the vegetation coverage in the basin to a certain extent [31] and reduce soil erosion. At the end of the last century, extensive sand mining caused Fudu River to become shallow. To ensure the river landscape and environmentally friendly water use, rubber dams had been built in the river. These actions will help trap sediments upstream. All the above factors have decreased the sediments flowing into the sea by rivers to varying degrees, and caused insufficient sandbar source material, resulting in shrinkage.

4.3. Prediction of Evolution Trend

As indicated by the remote sensing imaging interpretation, the extension rate of the sandbar has been relatively stable over the past decade, averaging 49.5 m/a. Based on the relationship between the year and the distance from the head of the sandbar to the coast, a simple linear regression model was established (Figure 8). The sandbar was estimated to extend to the present coast in 2–3 years (2023–2024), and in that case the semi-closed lagoon will become a closed lagoon. As a matter of fact, the lagoon had undergone a closing process in 2000. The closure of the lagoon is the inevitable natural evolutionary result of the sandbar under the control of the specific wave characteristics in the study area. With the narrowing of the lagoon entrance, the tidal current and wave action in the lagoon will gradually weaken and disappear, the dynamic environment will become increasingly mild, and the sedimentation will gradually change to fine grain deposition. Increased argillaceous sediments in the study area have been detected [32]. In 2019, part of the coast on the north side of the estuary was reinforced as a seawall. Although the seawall can protect the coast from erosion, it also weakened the sand supply for the sandbar on the east side.

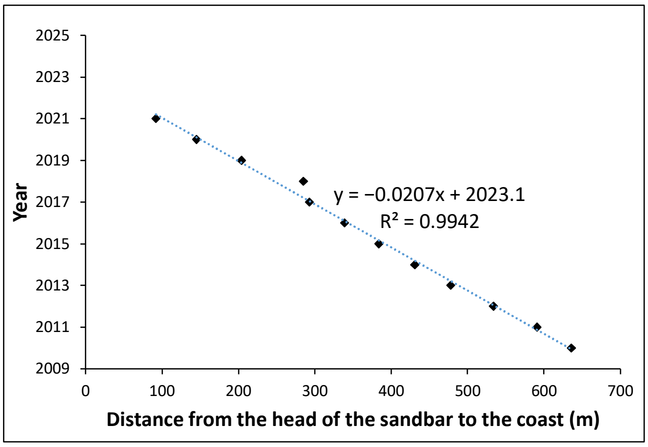

Figure 8. Linear regression relationship between the year and distance from the head of the sandbar to the coast.

4.4. Suggestions for Conservation and Restoration

The analysis of the controlling factors of recent geomorphological evolution shows that the extension of the sandbar is the result of natural evolution under regional wave dynamics, so it is unwise to fight against it. However, the retreat of the sandbar is mainly caused by human factors and can be weakened by manual intervention. The following interventions are recommended to protect FESL.

(a) Demolish the dam on the east side of the estuary. After doing so, the path of material movement from the river to the sea can be unblocked, and material supply in the east of the dam can be restored.
(b) Demolish the dam on the east side of the estuary. Due to the trend of sediment transport from SW to NE, an illegal estuary dam blocks the coastal transport path of sediment into the sea, which is the main reason for the lack of material supply in the northeast of the sandbar. Once the dam is demolished, the supply of materials for the northeast of the sandbar can be restored and the retreat of the sandbar can be weakened.
(c) Demolish the dike within the lagoon. This paper argues that the extension of the sandbar is the result of natural evolution under the condition of wave dynamics, and the dike in the lagoon will not help prevent the extension of the sandbar to the coast, but rather shields the interior of the sandbar. After demolition of the dike, the dynamic conditions on both sides of the sandbar can be restored to their original state.
(d) Demolish the dike within the lagoon. The dike within the lagoon separates the water in the lagoon from the sandbar, making the sandbar unable to be affected by the hydrodynamic conditions in the lagoon. Once the dike is demolished, the dynamic conditions on both sides of the sandbar can be restored to its original state.
(e) Manual sand replenishment. The retreat of the sandbar leads to the degradation of the pro-sea quality of the bath. To some extent, appropriate manual sand replenishment can quickly restore the leisure value of the bath. If manual replenishment is adopted, replenishment on the east side of the artificial island is recommended. Sediments are gradually transported eastward under natural conditions, relieving erosion of the sandbar to a certain extent. Manual replenishment can however only be used as a supplementary measure. Demolition of the estuary dam and restoration of the provenance supply are the most effective options.

4.5. Shortcomings and Prospects

The research based on remote sensing images in this paper is two-dimensional and cannot reflect changes in the height of the sandbar. Therefore, continuous elevation measurement of the sandbar would be an effective method for in-depth research.

As the sandbar on the north side of the estuary has been connected to the current coast, it has evolved into a compound sandspit. As pointed out in Section 4.3, the sandbar had undergone a process of closure in 2000. In addition, there are many remnants of early sandbars. Although the remote sensing changes have not been obvious in the past 10 years, research based on larger time scales (for example, interdecadal) will be meaningful.

5. Conclusions

This paper reports for the first time on the recent geomorphic evolution of the Fudu Estuary Sandbar Lagoon. Based on interpretation of high-resolution remote sensing images, it illustrates the changes in its geomorphic parameters from 2010 to 2021. In combination with the calculations of wave sediment transport along the coast, patterns of material transport in the sandbar area are studied, the response of shoreline erosion to coastal construction projects is analyzed, and the factors controlling the geomorphic evolution are discussed. Lastly, the future evolution of FESL is predicted, and suggestions for its conservation and restoration are put forward. The following conclusions were drawn from the study.

(1) Over the past decade, the sandbar has been extending toward the coast at an average speed of 49.5 m/a. The coastal sediment transport calculation shows that W-oriented waves are the hydrodynamic basis for the rapid extension of the sandbar, and the extension is the result of evolution under natural conditions.

(2) Over the past decade, the sandbar shoreline has been eroded and retreated by 25–45 m, and the annual new growth has shown a decreasing trend in area and width. The migration of the sandbar section responded well to the construction of the estuary dam and artificial island. The constructions block the sediment transport path in the surf zone, which is the hydrodynamic factor of sandbar shrinkage. The decrease in river sediment input is the provenance factor for the shrinkage.

(3) The recent geomorphic evolution of the Sandbar-Lagoon is the result of the combined action of natural conditions and human activities. It is estimated that the sandbar will extend to the current coast in 2–3 years (2023–2024), and the lagoon will be closed. In order to alleviate the shrinkage of the sandbar, it is recommended to take measures such as dismantling the estuary dam and restoring the sediment supply from the Fudu River.

Author Contributions: Conceptualization, L.Z.; methodology, P.W. and C.Z.; formal analysis, J.Y.; investigation, L.Z., P.Z. and J.Y.; writing—original draft preparation, L.Z. and B.Z.; writing—review and editing, P.W., C.Z. and Y.Y.; visualization, J.Y.; supervision, P.Z.; and funding acquisition, X.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the National Natural Science Foundation of China (No. 51809052), the Foundation of State Environmental Protection Key Laboratory of Marine Ecosystem Restoration (No. 202106) and the Doctoral Scientific Research Foundation of Liaoning Province (No. 2021-BS-300).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: The authors would like to thank the editors and reviewers for many constructive suggestions and comments that helped improve the quality of the paper.

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

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