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RESEARCH

Study on coastal sediment budget imbalance in cells resulted from land cover change in the savanna desertification area, west Hainan Island (China)

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Abstract

Coastal zone construction has developed rapidly in recent years in the western region of Hainan Island (China). The study area is the only savanna desertification zone in China which has been suffering severe coastal erosion and accretion in the past 2 decades. To better adapt to the environment of coastal area and protect its resources, we must understand its sedimentary environment fully. This work was based on collecting environmental data and analyzing climatic factors in the study area to better understand the processes of sediment dynamics. Field observation was carried out in the study area, with satellite image analysis and software simulation; detailed studies were made on the evolution process of the shoreline, the stability of the shoreline and the sediment level in the last 20 years. On this basis, the conceptual model of sediment transport is presented, and the coastal dune can be used as a transport engine to drive sediment migration between coastal cells and maintain the stable development of the coastal area. Under the same dynamic conditions, when the forest replaces the natural coastal dunes, the sediment transport path is blocked. This will cause accumulation on the upstream flank and erosion of the downstream flank. Coastal geomorphology, including beach in tidal area and dunes along terrestrial zone, has been undergoing severe change in study area in the past 2 decades. Humans tend to change the natural environment according to their interests, and the feedback mechanism of the natural environment is often characterized by the hysteresis effect, which is not worth losing in the long run. We must respect nature and reduce unnecessary environmental damage.

Keywords Sediment transport · Costal stability · Coastal area · Coastal erosion and accretion

1 Introduction

Coastal erosion and accretion have always existed and these processes have contributed to shaping the present coastlines. However, regional coastal erosion and accretion are now intensified due to improper human activities, resulting in the loss of resources of sediment and habitat. The annual cost of mitigation measures is not acceptable. Nevertheless, our remedial actions often fail to achieve the desired effect or have the opposite influence (van Rijn, 2010; Luo, 2015, 2016).

Researchers have proposed the concept and theory of coastal sediment management in recent years. They believe that managing erosion and accretion in the coastal zone is done through sediment management. This requires (1) keeping coastal resilience, (2) utilizing the theory of coastal sediment cells, (3) having favourable sediment status and (4) sustaining strategic sediment reservoirs (European Commission, 2004). After more than 10 years of experience accumulation, the concept of coastal cell and sediment management has been deeply rooted in people's minds and has been well applied (Anfuso, 2011; Mulder, 2011).

This study attempts the coastal cell theory in China's coastal zone. The study area is in Changjiang County in the west of Hainan Island (see Fig. 1), the only tropical savanna desertified coastal zone in China. According to the coastal sediment cell theory, the two headlands convert the study area into three relatively independent cells: cell-1, cell-2 and cell-3. Twenty years ago, there was a

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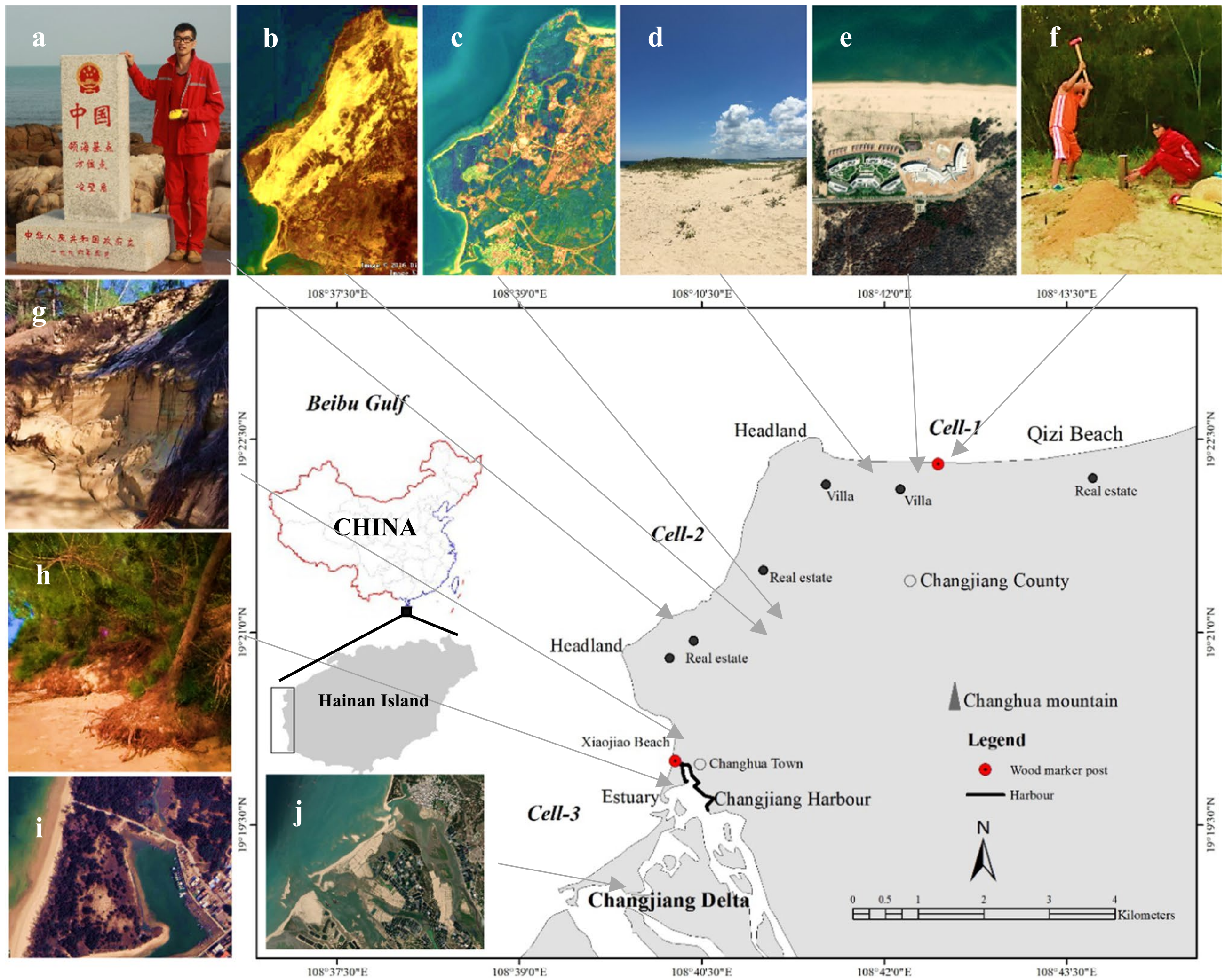

Fig. 1 Location map with major coastal constructions, coastal erosion pictures, logpile and profiles used in the study. Pictures show: **a** azimuth stele, **b** coastal dunes (yellow, year 2000), **c** coastal forest (dark color, year 2021), **d** coastal dunes, **e** real estate and Villa, **f** wood marker post, **g** erosion scarp, **h** naked root, **I**, **j** harbor and delta

northeast-to-southwest strip of desertified land between cell-1 and cell-3, about 4,500 m long and 1,500 m wide (see Fig. 1b). Now the desertified zone has been replaced by coastal shelterbelts (see Fig. 1c). The possible sediment sources in coastal cells include: river delta transport, coastal dune transport, offshore transport from the shelf, alongshore transport, and bio-deposition. Important sediment sinks include aeolian coastal dune transport, coastal current transport, sand mining, and offshore transport. The desertified land zone is a sediment transport corridor connecting coastal cells and acts as a sediment source-sink for the two coastal cells. In the past 20 years, vegetation coverage in the study area has increased significantly, and land desertification has been significantly improved. However, shelterbelts have blocked sediment migration among coastal cells, resulting in imbalance of sediment budget within the cells, accretion upstream (see Fig. 1d) and erosion downstream (see Fig. 1g, h).

In recent years, a large number of excellent research results have been published in study area, mainly focusing on three directions: the causes and mechanisms of desertification in the western part of Hainan Island (He, 1980; Guo, 1982; Li, 2005, 2006, 2007; Wu, 2022); Land use and cover change and its driving mechanism in the study area (Ou, 2013; Ni, 2016); Marine sediment characteristics and sediment transport trend in the study area (Chen, 2014; Gao, 2014; Zhou, 2016a, 2016b; Lv, 2021; Wang, 2022). The physical and geographical conditions, land use and cover change, and sedimentary process in the study area are recorded and referenced.

With the intensification of global climate change, extreme marine disasters and natural disasters are becoming more frequent. To reduce the loss of people's lives and property, it is particularly important to study the process of change in coastal resources (sediments and habitat).

The main concerns of this study are as follows: (1) characteristics and change process of the sedimentary environment in the study area, including geographical conditions, climatic conditions, land use and cover change; (2) shoreline evolution, stability, coastal sediment budget; (3) build the conceptual model of coastal sediment budget, discussing the relationship between coastal erosion and sediment supply, based on coastal cell theory and; explore the effects of land cover change on the sediment transport pathway.

2 Study area

2.1 The physical environment

2.1.1 Geographical environment and monsoon

The west of Hainan Island is located on the west side of the Five-Finger Mountains (the highest peak is 1867 m), which is the rain shadow area of the South China Sea monsoon. At the same time, it is located in the northeast of Truoun Son Ra of Indo-China Peninsula (the highest peak is 2598 m), which is the rain shadow area of the Bay of Bengal monsoon (see Figs. 2, 3).

Under the influence of the intersection and superposition of two rain shadow areas, the drying and heating effect in the west of Hainan Island is strengthened, resulting in Foehn effect, which creates a typical tropical semi-arid climate and a fragile savanna environment. At the same time, it has the.

power, space and provenance of land desertification, making the west of Hainan the only tropical savanna desert coast in China, with a length of 170 km and; a width of 3–20 km long strip (see Figs. 1b, 2) (Xu, 2002; Li, 2005, 2006, 2007).

2.1.2 Climatic characteristics

Located in the northern part of the South China Sea, Hainan Island has a tropical monsoon marine climate. The annual mean temperature, rainfall, sunshine hours and drought frequency are as follows:

The annual average temperature in Hainan Province ranges 23–27 ℃, showing a circular distribution of low temperature in the middle and high temperature on all sides. The southern region is higher than the northern region, and the coastal region is higher than the inland region. In the desertified area of western Hainan, the highest temperature was higher than 25 ℃ (see Fig. 4a). The annual rainfall of Hainan Island ranges from 900 to 2300 mm, with a circular distribution. The center is located on the windward side of the eastern Five-Finger Mountains. The annual rainfall in the western coastal areas is less than 1000 mm, only half of that in the eastern rainy areas. The rainfall in the west desertified area of Hainan Island was the lowest in the whole island (see Fig. 4b). The annual sunshine duration of Hainan Island is between 1800 and 2700 h. There are two low-value centers in the south and north of the island, and the sunshine duration is less than 1900 h. In the western and southern areas, the sunshine duration is above 2200 h, and the desertification area in the west of Hainan Island is the highest (Fig. 4c). The drought frequency in Hainan Island is high in the west and low in the east. The drought frequency in Dongfang City in the western desertic area is the highest, reaching 74%, while the frequency in the eastern part of the Five-Finger Mountains is relatively low (see Fig. 4d) (Zhang, 2019; Wu, 2022).

Generally speaking, due to the above rain shadow effect and Foehn effect, the desertified area in the west of Hainan Island has higher average annual temperature, less rainfall, more sunshine duration and higher annual drought frequency. These factors are the necessary conditions for desertification.

2.1.3 Regional sediment transport conditions

According to the analysis of the data from the ocean observation station of western Hainan (1988–2007), wind wave in the study area accounted for about 62.4%, and the high frequency of wind waves were SSW and NNE, accounting for 15.9% and 11.2%, respectively. Swells accounted for 37.6%, and SW had a high frequency, accounting for 10.3% (Zhang, 2014). The strong wave directions were SSW, NNE and SW, accounting for 18.8%, 14.3% and 12.4%, respectively, and the wave heights were all above 0.5 m (see Fig. 5, Zhou, 2016b).

Changjiang River is the main river in the west coast of Hainan Island, and a delta of sandbanks, marshes is developed in the estuary area (see Fig. 1j). An underwater spit extending to the southwest at 5 m isobath shows the migration trend. Controlled by the headland, the waves of NE and NW cannot propagate southward, and have a blocking effect on the drifting sand from north to south (Zhang, 2014). At the same time, the southwest-trending coastal current caused by the clockwise circulation of the Beibu Gulf also played an important role in sediment migration to the southwest direction (Gao, 2014).

2.2 The coastal land cover change

2.2.1 Coastal vegetation coverage

Zhang (2009) studied the spatio-temporal variation characteristics of desertification in the western part of Hainan Island in the last 50 years (1959–2003), and believed that the area of desertified land in Hainan Island was greatly reduced

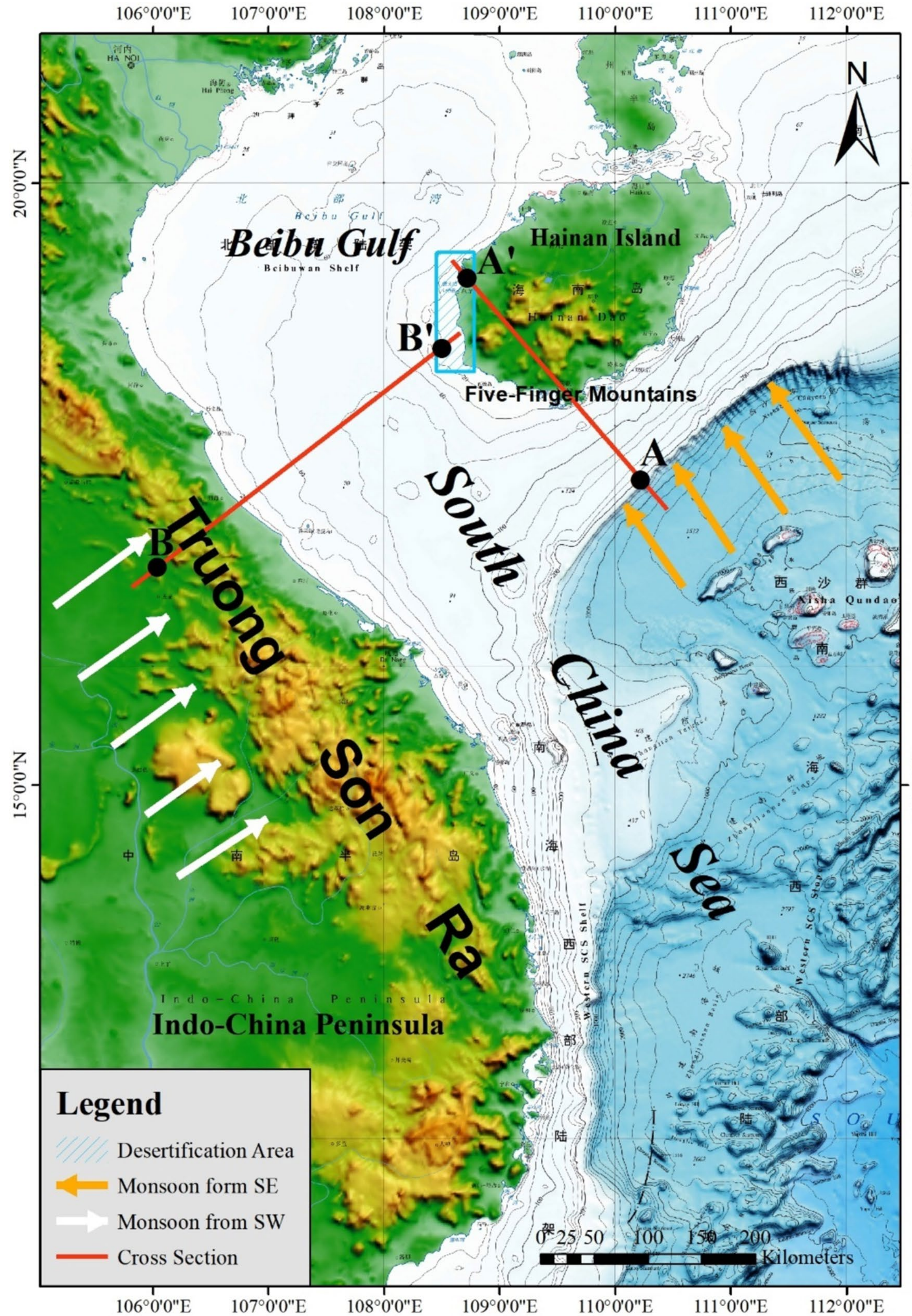

Fig. 2 Map of desertification area and monsoon route in western Hainan Island

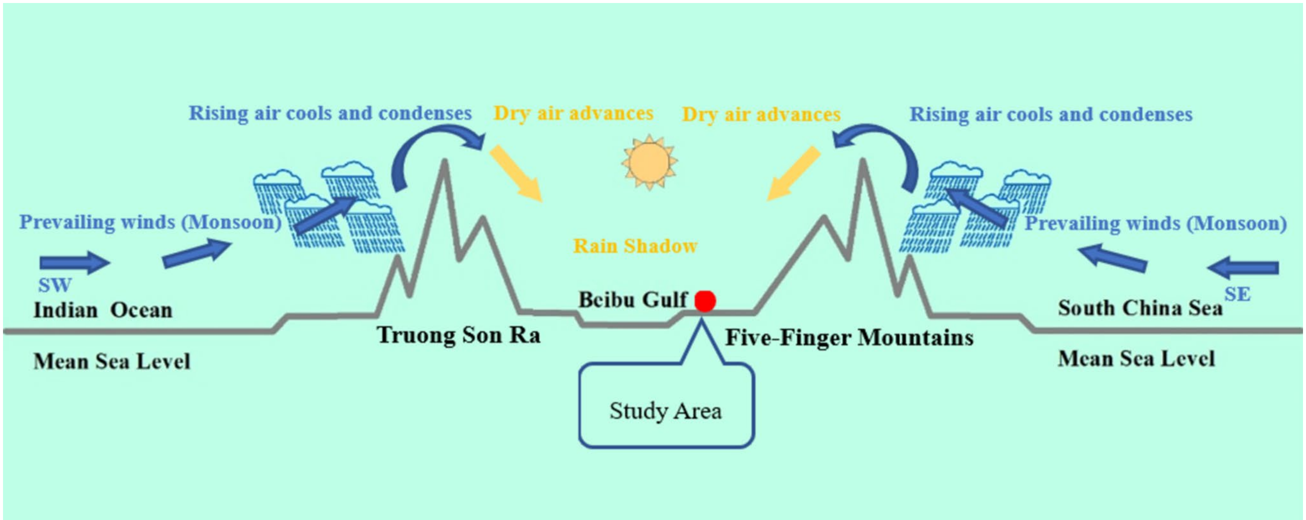

Fig. 3 Rain shadow formed by monsoon (the position of cross section, seeing Fig. 1 A–A′, B–B′)

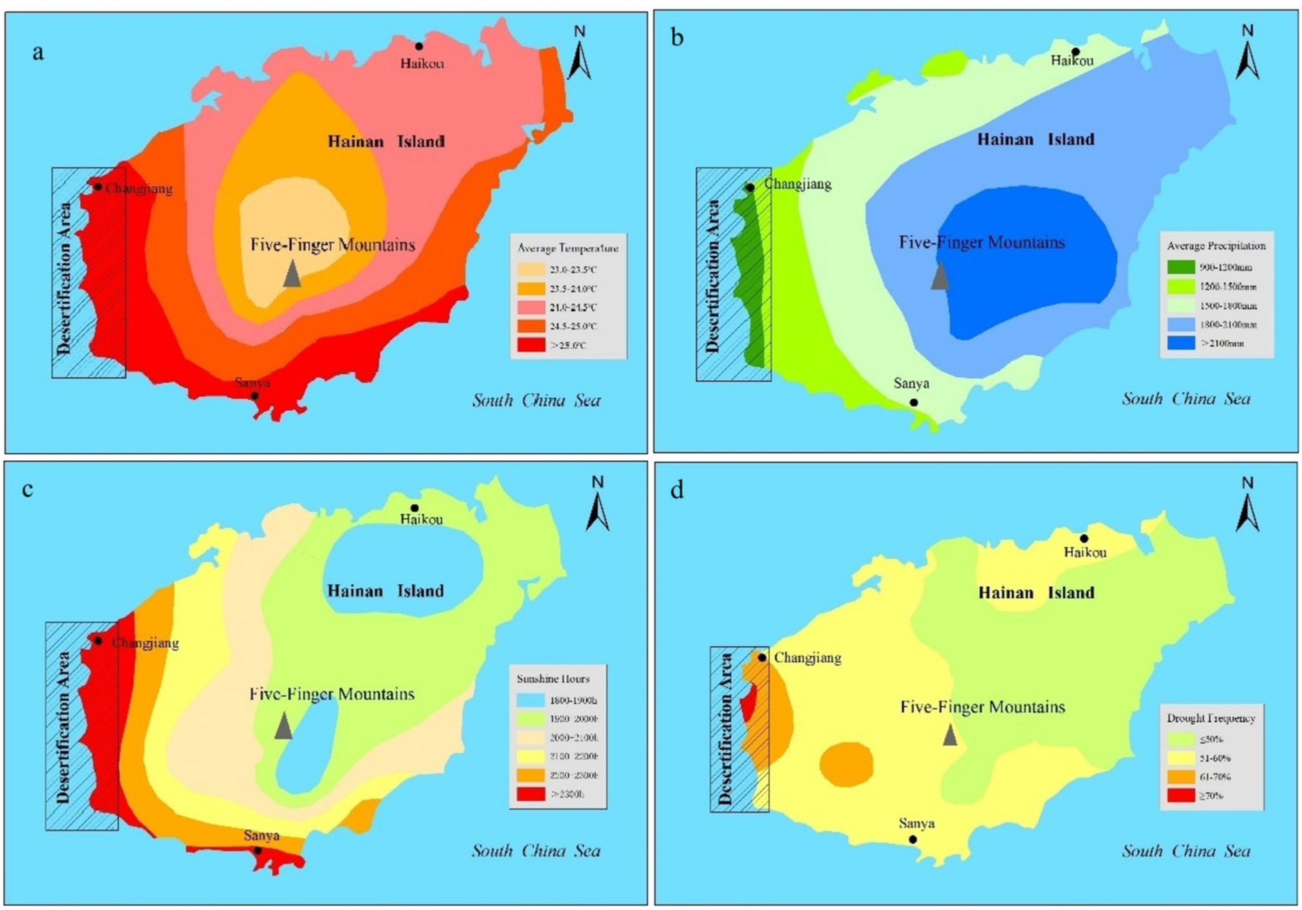

Fig. 4 Hainan Island climate characteristics, highlighting "Desertification Area" situated at western Hainan Island (a—temperature, b—precipitation, c—sunshine hours and d—drought frequency. Modified from Wu, 2022; Zhang, 2019)

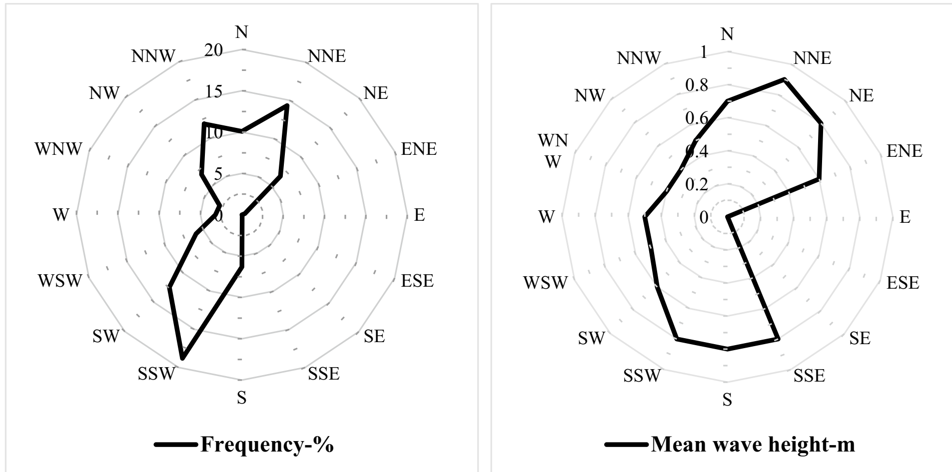

Fig. 5 Wave (left) and mean wave height-H_s (right) rose near study area cape of 10-year investigations (derived from Zhou, 2016b; Chen, 2014, modified)

and the degree of desertification was reduced. To study the spatial characteristics of desertification in the western part of Hainan Island, Ni (2016) calculated the standard deviation of EVI (Enhanced Vegetation Index) in the western part of Hainan Island from 2001 to 2014 based on pixel by pixel of remote sensing images. The vegetation changes in the western part of Hainan Island showed obvious spatial differences, and the low-value areas were mainly distributed in the inland areas. The high-value areas are mainly in the northern coastal zone, where vegetation cover is low, human activities are strong, and changes are relatively drastic (see Fig. 6a). The change trend of EVI was also calculated: the

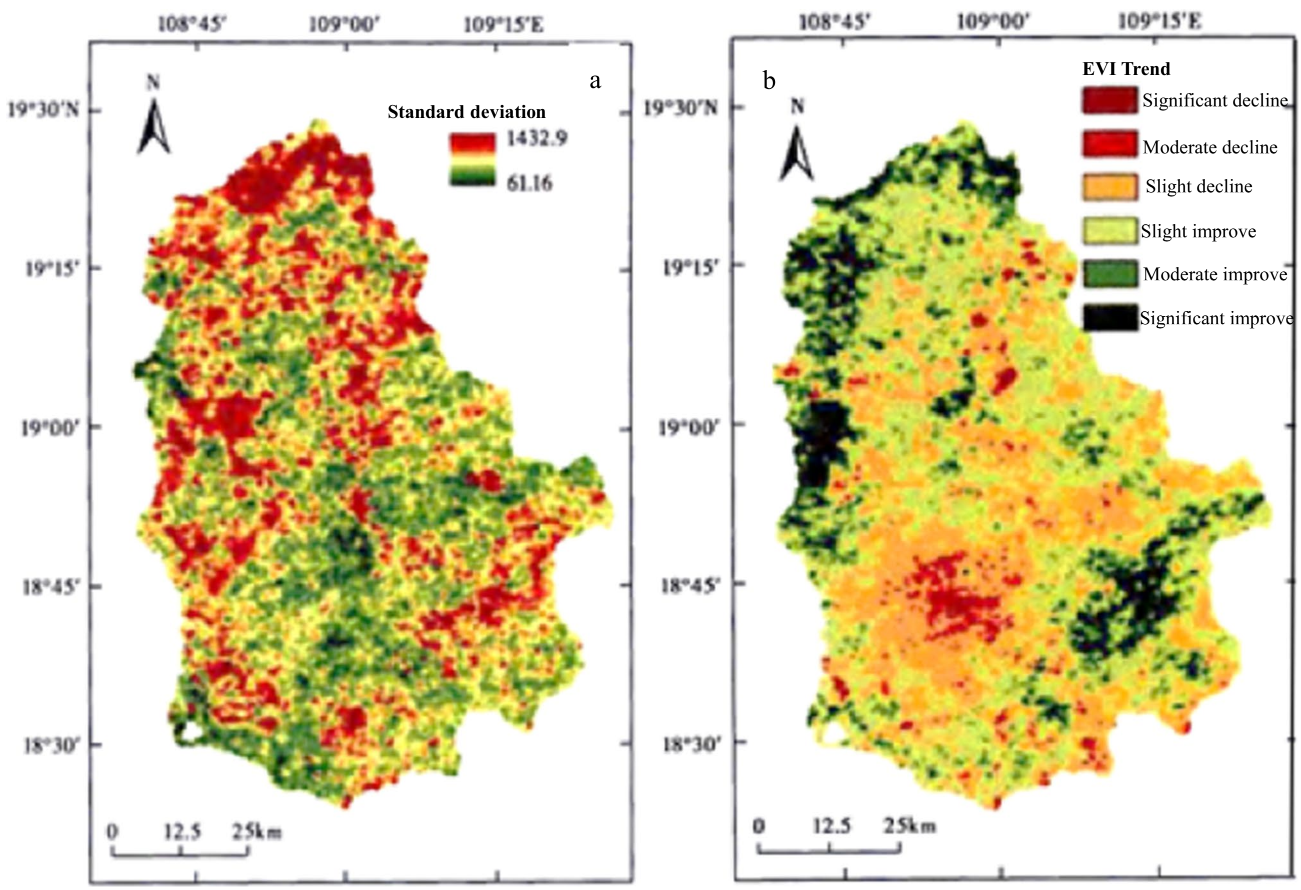

Fig. 6 Spatial distributions of EVI standard deviation (**a**) and EVI trend (**b**) in western Hainan Island desertification area (see Fig. 2 and Fig. 4) during 2001–2014 (Ni, 2016, modified)

vegetation cover in the west of Hainan Island showed an overall upward trend, and the area of the trend increase accounted for 65.2%. The areas with significant and moderate improvement reached 8.54% and 8.69%, respectively, mainly distributed in the northern and western coastal zones, which indicated that the desertified land in these areas had been significantly improved (see Fig. 6b).

2.2.2 Coastal occupation

Changhua fishing port plays an important role in the development of marine fishing industry in Hainan Province. However, under the influence of factors such as sediment accumulation and quicksand backfilling for a long time, the channel of the fishing port becomes narrower and shallower year by year, resulting in serious safety risks (see Fig. 1i). In 2014, the importance of building a first-class fishing port in Changhua was demonstrated (Chen, 2014). In 2023, upgrading and reconstruction of the fishing port began, including the construction of breakwaters to the north and south, dredging of harbour ponds and construction of wharves. The newly built fishing port can meet the production, berthing and wind shelter needs of 600 large, medium and small fishing boats in the surrounding areas of Changjiang River. It can also meet the needs of 40,000 tons of fish unloading, laying a foundation for the comprehensive development of "Dongfang-Changjiang" fishing port economic zone.

With the change of land use and cover in the study area, real estate, tourism, transportation and infrastructure also developed rapidly (see Fig. 1e). In addition, the research area has the territorial sea base point azimuthal tablet, wooden plank road and other beach occupied facilities.

3 Materials and methods

This paper used the following methods to investigate the study area (108°39′50″–108°44′32″E, 19°19′40″19°22′36″N):

1) Literature research and data inquiry. This paper collected the research results since the 1980s, summarized the previous work in the study area, described the evolution of the geographical environment, land cover change, climate characteristics, and hydrodynamic environment of the study area, and put forward the problems existing in the study area.
2) The evolution process of the shoreline of study area in recent 20 years was obtained by comparing satellite images. The images were downloaded from Google Earth and BIGEMAP software.
3) Field monitoring was carried out, which used RTK combined with total station to monitor the landform change and coastal erosion of fixed profiles in 2015, 2016 and 2022. We used wood marker post to monitor profiles perpendicular to shoreline for 7 years, then plotted the results in one print.
4) MeePaSoL software was used to fit the static equilibrium form of the coastline and predict the evolution trend of the coastline, basing on a statically balanced parabolic morphology model. You can get the software and instructions from the published paper (Lim, 2022).
5) Using sediment cell theory, the conceptual model of sediment migration in coastal cells in the study area were analysed (European Commission, 2004; Anfuso, 2011; Mulder, 2011).

4 Results and discussion

4.1 Shoreline change

Figure 7 shows the changes of shoreline in the downstream direction of the study area. The green line on the left is the vegetation line in 2000 (the boundary between beach and shelter forest), the blue line in the middle is the vegetation line in 2009, and the right is the vegetation line in 2021. Compared with the year 2000, the coastal erosion significantly increased, indicating that coastal erosion continued to occur, with the southern end experiencing the most severe erosion at rate of 5.6 m/a (see Fig. 8). At the same time, it can be observed from the three panels in Fig. 7 that the land use/cover changes in the coastal zone started with coastal dunes (in the year of 2000), passing through large-scale afforestation in 2009. In 2021, shelterbelts were created covering the entire coastal zone, with no trace of coastal dunes. We have a vague sense that coastal erosion and siltation are closely related to changes in coastal land cover.

Fixed monitoring piles and monitoring profiles also show beach erosion or siltation. Interannual monitoring of beach profiles downstream of the study area shows that beach erosion has continued since 2015, with a maximum erosion rate of 0.2 m/year in the intertidal zone, which is a serious erosion (see Fig. 9). The monitoring profile in the upstream direction shows slight siltation (see, Fig. 10).

4.2 Coastal stability

At the beginning of shelterbelt construction in 2000, the predicted shoreline and vegetation line coincided well, indicating that the beach was in a state of dynamic balance. After the completion of the shelter forest in 2021, the actual shoreline is located on the landward side of the predicted shoreline and is unstable (see Fig. 11). Due to the existence of the headland, the NE and NW waves cannot propagate southward. After diffraction through the

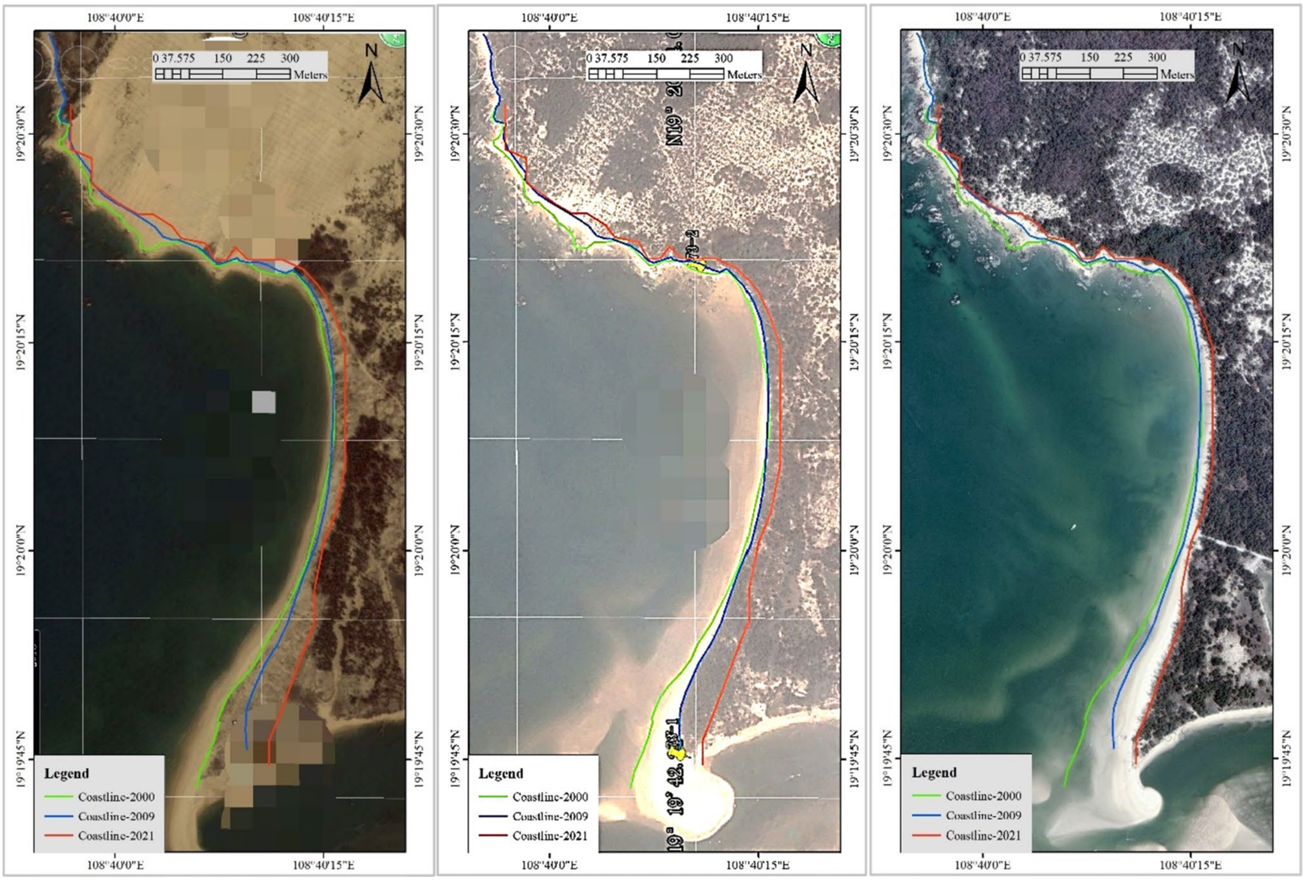

Fig. 7 Coastline evolution (beach rotation) and land cover change of year 2000, 2009 and 2021

headland, the waves incident on Xiaojiao beach toward about NW284°. Meanwhile, influenced by the waves in the direction of SSW, the present shoreline planform and beach profile are shaped.

In terms of coastal stability, headland-bay beaches may be classified as being in static equilibrium, dynamic equilibrium and unstable. Static equilibrium is reached when the predominant waves are seen to be breaking simultaneously around the whole bay periphery. At this stage, littoral drift is almost non-existent, and the curved beach is stable without long-term erosion and deposition. For bays in dynamic equilibrium, balance in sediment budget is the key factor in maintaining the shoreline in its existing position. However, coastline in dynamic equilibrium could retreat if sediment supply reduces from the upcoast or a river within the embayment, and recede to the limit defined by static equilibrium, if supply diminishes completely. Bays are classified as unstable, often resulting from wave sheltering by a structure added to the beach, the curved shoreline experiences accretion in the lee of the structure accompanied by erosion downcoast in the process of natural reshaping (Klein, 2003; Li, 2006).

4.3 Coastal sediment status

4.3.1 Favourable sediment status-before the year 2000

According to the theory of coastal cell, the study area can be formed into three cells, and the sediments in this area are mainly transported to the southwest under the influence of coastal currents and wind-driven sediment transport (see Fig. 12). When coastal dunes were typical of land cover, the sediment budget of each cell was balanced and the entire coastline was stable, with neither erosion nor siltation. The sediment source of Cell-1 is mainly the westward coastal sediment transport. Obstructed by the headland, the sediment is transported to the beach and dune, and the dune becomes the sediment sink of Cell-1. Cell-2 is mainly the bedrock shoreline of the headland, which is in a state of equilibrium or weak erosion for a long time, with a small amount of sediment transported to the southwest under the traction of the longshore current. Cell-3 mainly took the Changjiang River sediment supply as the sediment source, and the sediment was transported southward. At the estuary, a secondary cell can be delimited, and the sediment source

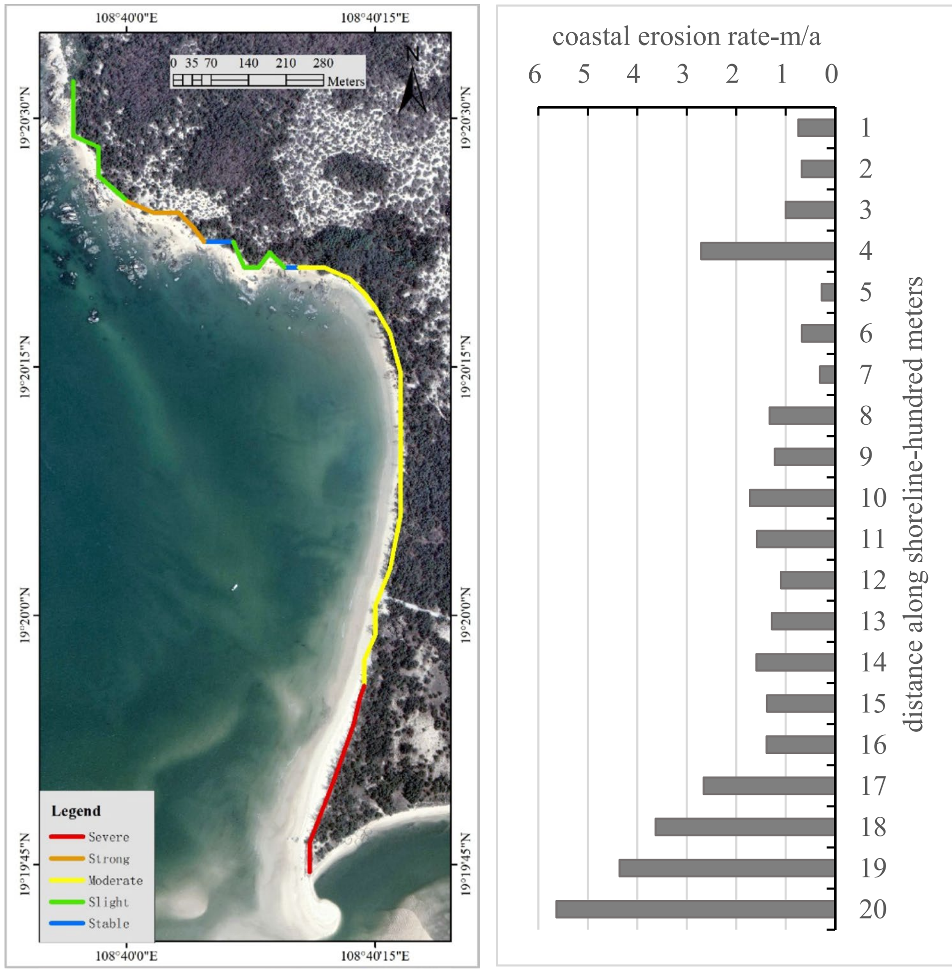

Fig. 8 Coastal erosion level (left) and rate (right) along the coast between 2000 and 2021

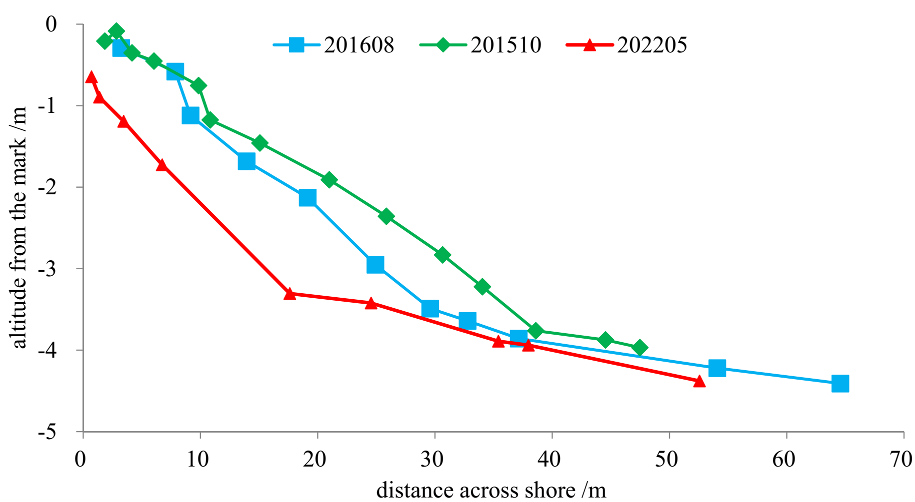

Fig. 9 Profile perpendicular shoreline topographical change (situated southwest, see Fig. 1)

of this sub-cell is the coastal dunes, and the sediment entering the unit is carried away by the coastal current, so that the unit is in dynamic equilibrium.

The study area can also be seen as a large coastal cell, a Mega-cell, in which the coastal dune is the sediment bank, temporarily storing the sediment. It also acts as a sediment transport corridor to transport sediments between secondary cells, maintain the coastal dynamic balance and keep the coastal unit sediments in a favourable sediment status.

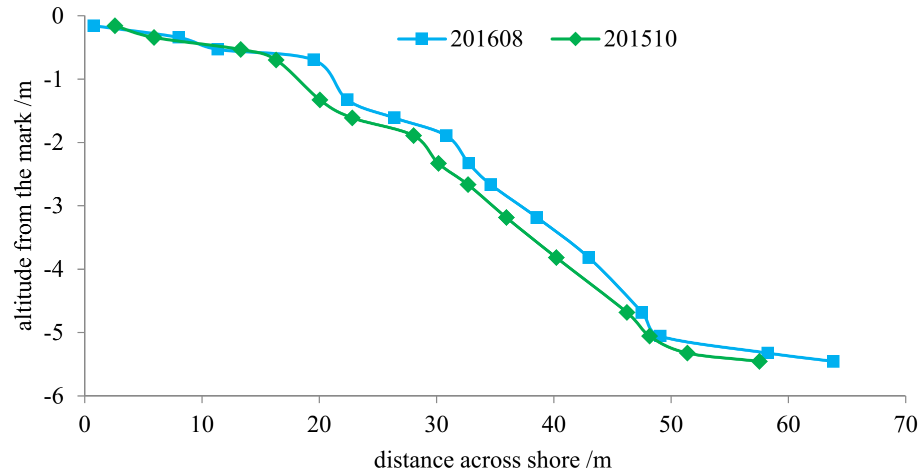

Fig. 10 Profile perpendicular shoreline topographical change (situated northeast, see Fig. 1)

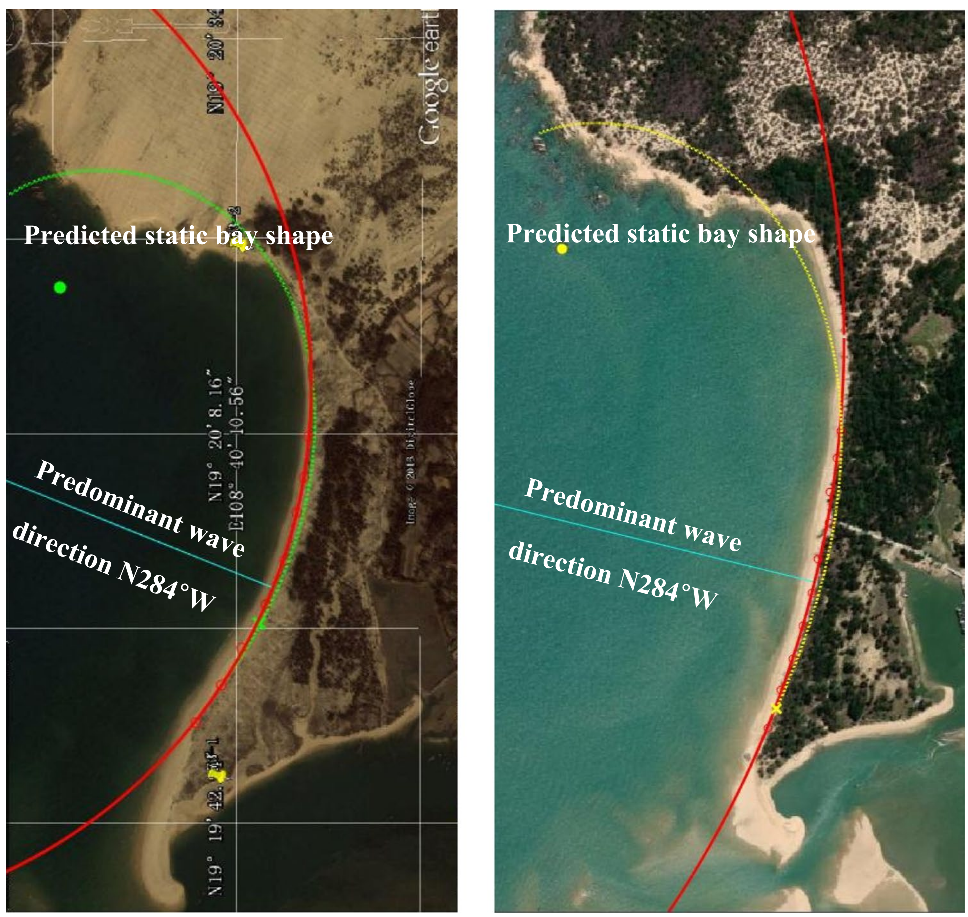

Fig. 11 Graphic results of shoreline planform of Xiaojiao beach using MeePaSoL software (left: year 2000, the coastline was stable; right: year 2021, the coastline was unstable)

4.3.2 Sediment budget imbalance-by the year 2021

In the Mega-cell mentioned above, great changes have taken place in the coastal zone in the past 20 years, such as rapid development of coastal erosion and siltation, coastal land use/cover changes, that is to say, the physical characteristics of the coastal zone have changed. However, during this period, the dynamic conditions of the coast, such as the southwesterly coastal current, the wave and wind conditions of the coastal zone, that is, the sediment source and sink conditions of the coastal cell, did not change. As shown in Fig. 13, the shoreline of Cell-1 is in a silted state, and

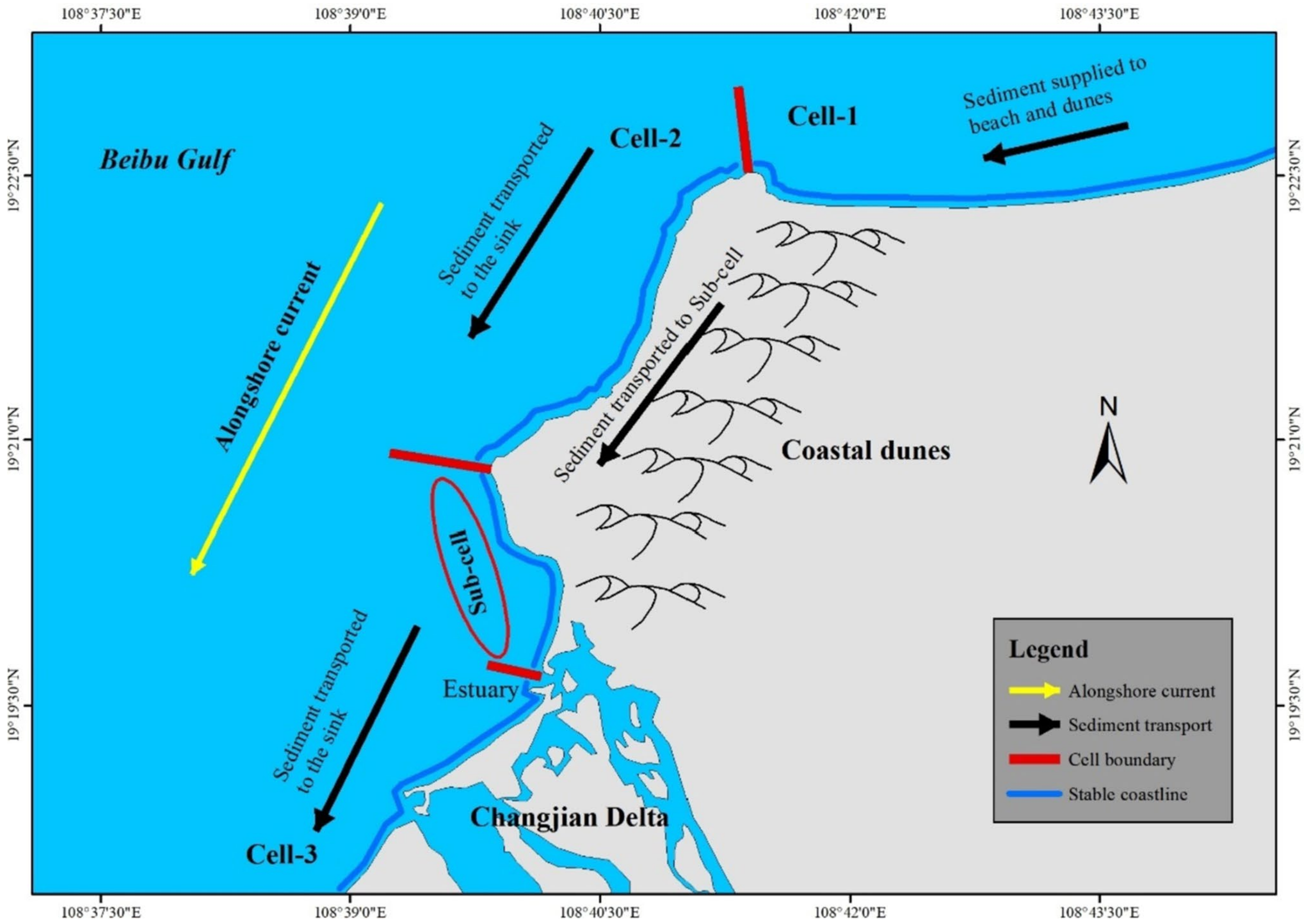

Fig. 12 Coastal sediment status at study area before the year 2000

obviously the beach becomes a sediment sink. Cell-3 is in an erosive state, indicating a loss of sediment sources. We found that coastal shelterbelts replaced the original coastal dunes, and that the south to north transport corridor had been blocked, thus finding the cause of upstream coastal siltation and downstream coastal erosion.

In addition to the ocean dynamics shaping the topography of the coastal zone, the aeolian activities cannot be ignored. When scholars talk about the causes of coastal erosion in Japan and Australia, they also mention that coastal dunes can provide sediments for beaches as transport corridors, and once the transport paths are blocked, erosion and siltation will occur (Uda, 2010; Hsu, 2021).

4.4 Conceptual models of coastal sediment transport

According to the above analysis, the coastal dune transport corridor can be used as a sand transport engine between the two cells to ensure the stable evolution of the coastline. Figure 14 shows the conceptual model between the cell-1 and cell-2 are coastal dunes. The sediment sources of cell-1 include sediment transport from coastal dunes (Q1-in-from dunes), sediment transport onshore (Q1-in-crossshore), and there is no longshore source supply due to the obstruction of the upstream headland. Sediment sinks include sediment transport to coastal dunes (Q1-out-to dunes), offshore sediment transport (Q1-out-crossshore) and alongshore sediment transport (Q1-out-alongshore). Cell-2 sediment sources include dune transport (Q2-in-from dunes), cross-shore transport (Q2-in-crossshore) and upstream coastal transport (Q2-in-alongshore). The sediment sink has sediment transport to the dune (Q2-out-to dunes) and offshore (Q2-out-crossshore), and there is no alongshore sediment transport out due to the obstruction of the downstream headland. According to the equation in the figure, the sediment budget is calculated and analyzed. According to the dynamic balance of shoreline, the sediment budget is conserved, that is $Q_{\text{-in}} = Q_{\text{-out}}$ ($Q_{\text{-in}}$, Quantity of sediment transported into cell in one year, $Q_{\text{-out}}$, Quantity of sediment transported out

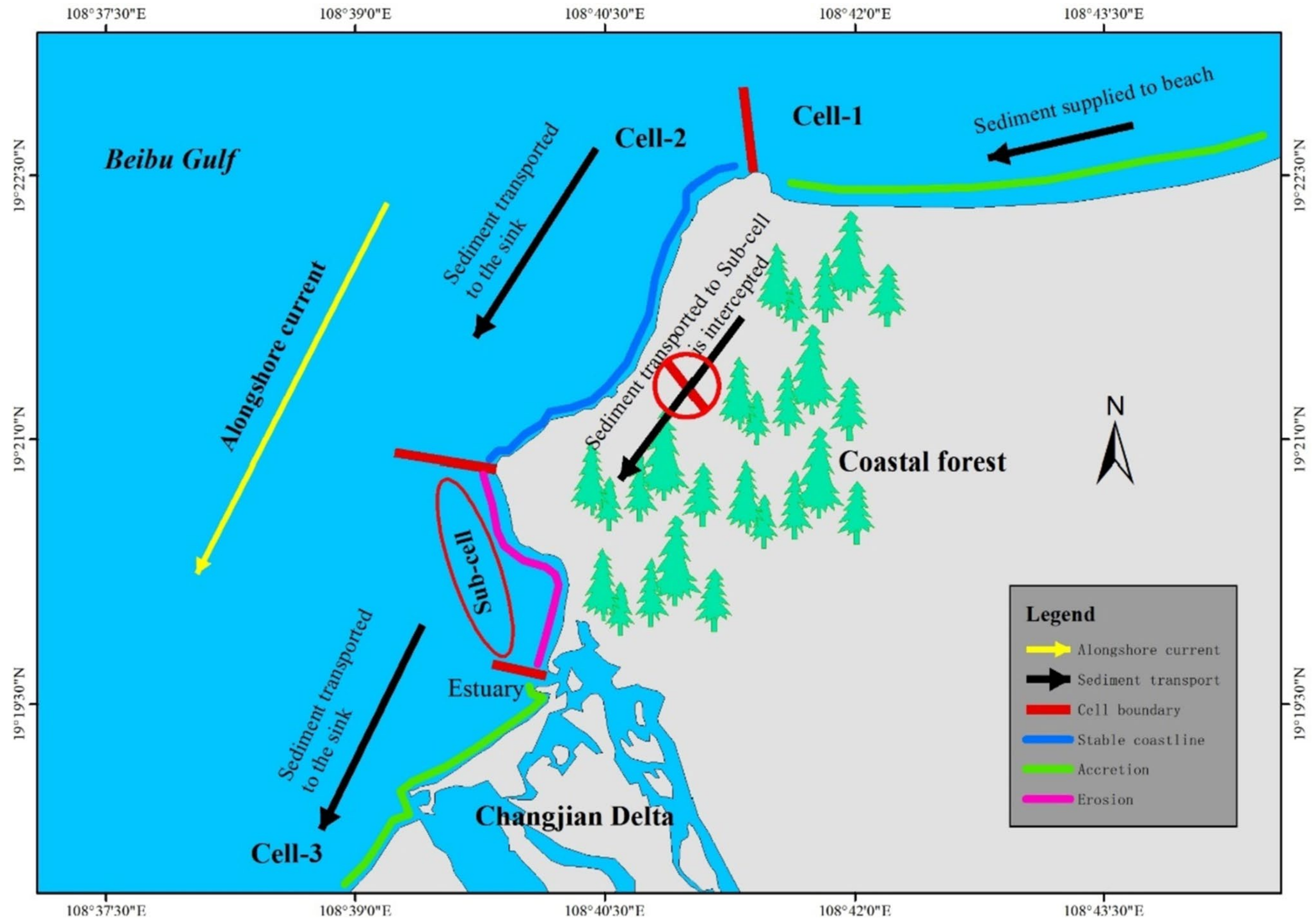

Fig. 13 Coastal sediment status at study area in year 2021

of cell in one year). Coastlines may vary seasonally, but the variation from year to year is negligible.

Figure 15 shows the conceptual model that shelterbelts replace the coastal dunes, the sand transport engine between Cell-1 and Cell-2 is shut down, and the development direction of the coastline is changed. Cell-1 lost the sand source supply from the coastal dunes, but the sediment sink did not decrease, and the sediment budget was unbalanced, that is, $Q_{-in} < Q_{-out}$, the beach erosion occurred, and the shoreline retreated. Cell-2 lost the dune as a temporary sink for storing sediment, but the sand source did not decrease, and the sediment budget was also unbalanced, that is, $Q_{-in} > Q_{-out}$. The beach silted up and the shoreline advanced to the sea.

5 Conclusions

The western Hainan Island has the geographical environment, climate and provenance conditions, making it China's the only tropical savanna desertification coastal zone. With the increase of human activities in the coastal zone, has an important impact on coastal zone environment. In particular, great changes have taken place in the coastal zone environment since the beginning of this century. The original coastal dune zone has been replaced by a coastal shelter forest. The change of land cover affects the sedimentary dynamic environment of the coastal zone, and then causes the change of the sedimentary environment of the beach. In

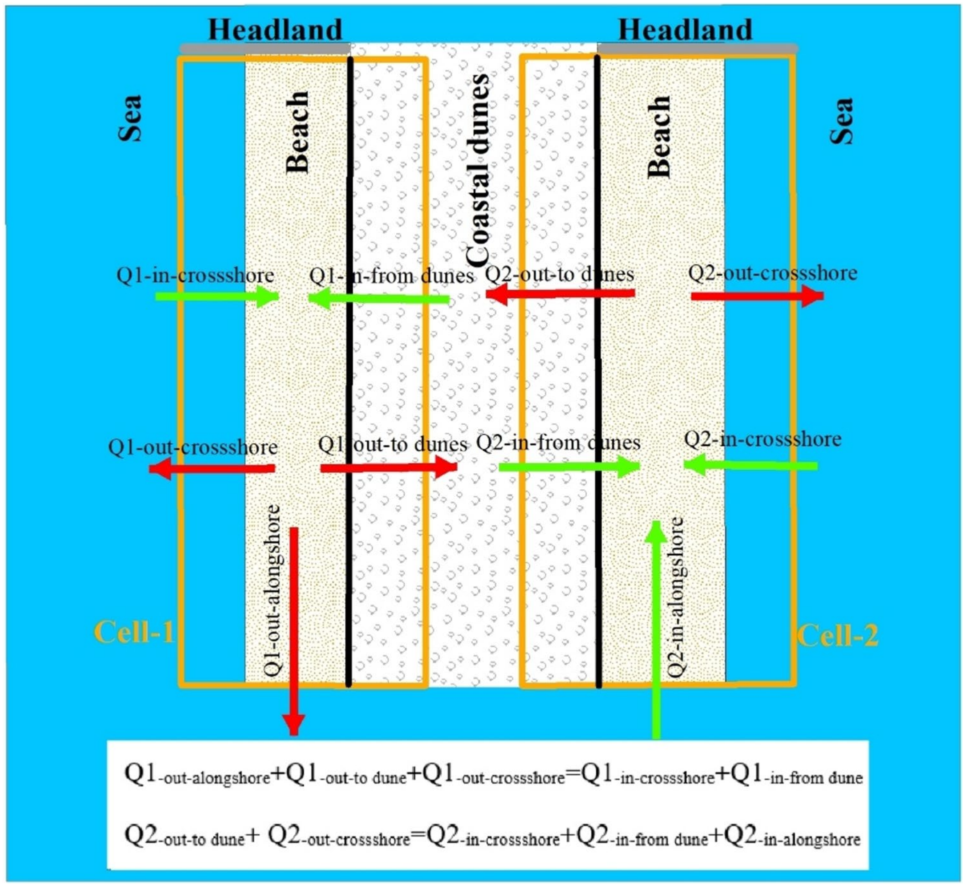

Fig. 14 Conceptual model of balance in sediment budget transported via coastal dunes between two cells (Q—quantity of sediment transport in a year)

the past 20 years, vegetation coverage in the study area has increased significantly, and land desertification has improved significantly. However, shelterbelts have blocked sediment migration among coastal cells, resulting in an imbalance of the sediment budget. The following conclusions are obtained through the research:

1) Since the year 2000, there has been a serious retreat along the downstream shoreline of the study area, and the monitoring of the beach profile also indicates obvious under-cut erosion and slight siltation in the upstream direction.
2) MeePaSoL software simulation results show that before the year 2000, the beach shoreline's downward direction in the study area was at a stable state, and now the beach is in an unstable state, indicating the evolution of coastal zone into the transition period.
3) The coastal cell theory is used to analyse the sediment budget level of the study area, which shows that the coastal dune can be used as the transport corridor of the coastal cell and maintain the dynamic balance of the two cells. Currently, however, coastal dunes have been replaced by coastal shelterbelts, which impede sediment transport between cells.
4) Two sediment transport conceptual models are presented in this paper, as a sand transport engine, coastal dunes drive sediment migration between cells to balance the annual sediment budget and maintain the dynamic balance of coastal units; when the dynamic conditions of ocean and land remain unchanged, the sediment migration path is blocked, and the sediment budget of coastal units is unbalanced, leading to erosion and siltation.

Humans tend to change the natural environment for their own interests, and the feedback mechanism of the natural environment is often characterized by hysteresis effect. Although people gain short-term benefits, they lose more than they gain in the long run. Mankind should advocate a planned, forward-looking and sustainable coastal zone development and management model, live in harmony with the natural environment, and minimize unnecessary environmental damage.

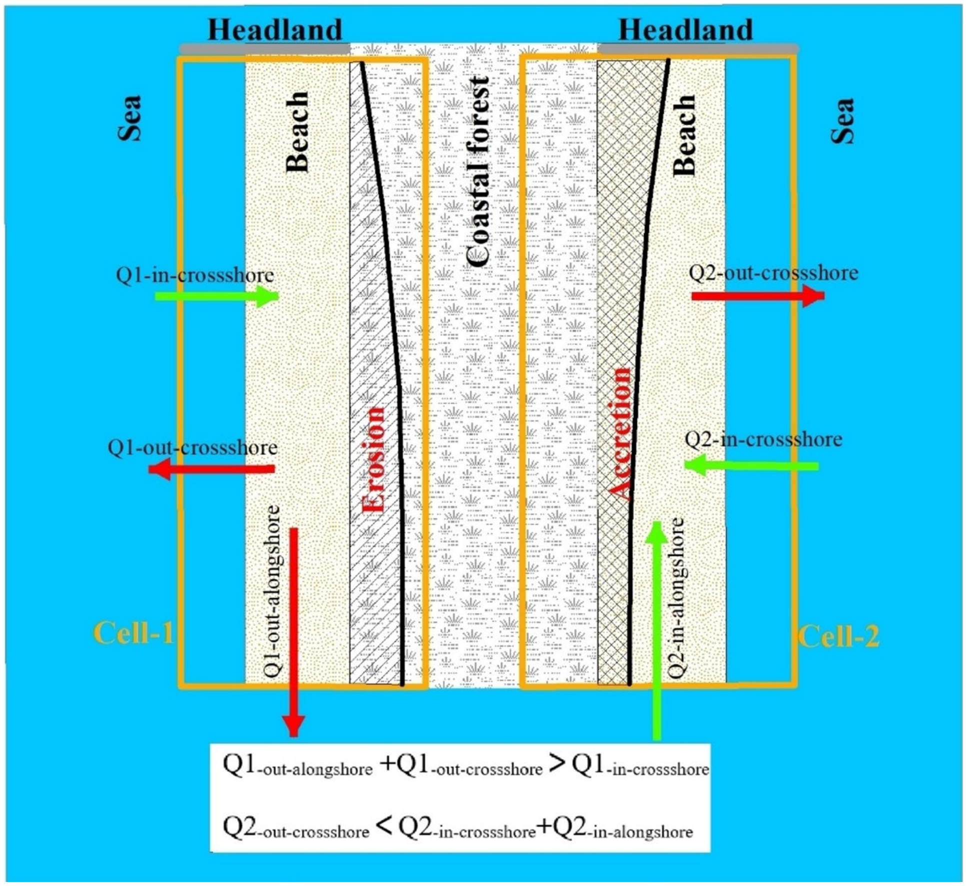

Fig. 15 Conceptual model of sediment budget imbalance for transport path intercepted by coastal forest between two cells (Q—quantity of sediment transport in a year)

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Author contributions Shilong luo wrote the main manuscript text.Ruifang Jin prepared the figures 1-15.Jiaxin Wang, Xinhao Wang, Manyu Huang, Mengjiao Peng, Shuolei Xu and Ruolin Zhao lanuched the field and lab work.

Data availability Data is available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

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