

## Coastal erosion risk assessment of Hainan Island, China

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### Abstract

Coastal erosion on islands is increasing due to sea level rise, frequent extreme events, and anthropogenic activities. However, studies on the multifactorial coastal erosion risk and the vulnerability of islands are limited. In this study, the Coastal Erosion Risk Assessment (CERA) method was applied for the first time to the study area in China to assess the erosion risk on the coast of Hainan Island; to explore the effects of coastal ocean dynamics, sediment movement characteristics, and anthropogenic construction; and to discuss the suitability of the method and countermeasures for coastal protection. The results show that the coast of Hainan Island shows high sensitivity, high value, low exposure, and moderate erosion. The whole island showed high vulnerability but low erosion risk, with the eastern region being more affected by erosion, particularly the eastern side of Wulong Port and Yalin Bay in Wenchang, and the shore section of Yalong Bay in Sanya, having a very high risk of coastal erosion. In addition, Monte Carlo simulation was used to check the applicability of the CERA method, and it was found that the rate of shoreline change, population density, and number of storms significantly contributed to coastal erosion, but only the short-term effects of sea level rise were considered. The effects of sea level rise and sediment grain size were primarily analyzed as influencing factors. The effects of sea level rise continue to strengthen, with coastal retreat expected to be greater than 2 m by the mid-21st century. Moreover, Hainan Island is primarily composed of the fine and medium sand types, which have little resistance to coastal erosion. Currently, the impact of sediment grain size is rarely considered in coastal erosion risk assessment studies. However, it can be incorporated into the indicator system in the future, and the spatial variation of indicators can be fully considered to strengthen the refinement study.

**Key words:** coastal erosion, Coastal Erosion Risk Assessment (CERA), vulnerability, risk, influence factor

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### 1 Introduction

Coastal erosion and siltation have always been present and have shaped the present coastline. Seventy percent of the world's sandy shores are eroded, and in many countries the eroded shoreline of sandy shores accounts for 60%–90% of the total shoreline (Sun et al., 2015). Coastal erosion is a global hazard that affects coastal areas around the world. It is mainly manifested as shoreline retreat and beach erosion due to the dynamic action of seawater. Since the 1950s, the extent of coastal erosion in China has been increasing, with approximately 70% of sandy beaches and silty tidal flats in open water in a state of erosion retreat (Xia et al., 1993). Therefore, for the comprehensive protection and utilization planning, disaster prevention, and sustainable development of coastal areas, it is necessary to analyze the coastal erosion risk in typical erosion areas.

Since the 1990s, researchers have conducted extensive and in-depth studies on the causes, processes, patterns, and management of coastal erosion. Coastal erosion hazard studies focus on the current situation, loss, causes, and future prediction of coast erosion (Xu et al., 2013; Luo et al., 2013; Rangel-Buitrago et al., 2020). However, the research on risk assessment of coastal erosion is limited (Xu et al., 2013). It is generally acknowledged large river deltas and islands as the most vulnerable areas to

coastal erosion, but related studies are still inadequate or not deep enough (Wang et al., 2021). Although there is no one assessment method that is applicable globally, there are several methods for coastal erosion risk or vulnerability assessment, such as Coastal Vulnerability Index (CVI), Smartline, RISC-KIT Coastal Hazard Assessment Module (CHAM), Coastal Hazard Wheel (CHW), and Coastal Erosion Risk Assessment (CERA) (Narra et al., 2019b; Bukvic et al., 2020; Anfuso et al., 2021; Paul and Das, 2021; Su et al., 2021). The basic idea is to group multiple indicators affecting the coastal zone ecosystem into a system that reflects a comprehensive situation for risk assessment. The constituent indicators of each method vary depending on the characteristics of the study area and the conceptual framework. Currently, the impact of human activities on coastal erosion is often considered consciously in the selection of indicators (Cai et al., 2022; Cao et al., 2022). The most commonly used indicators are wave conditions and geomorphological characteristics of the study area, followed by socioeconomic data. Compared to other methods, the CERA method is both basic and comprehensive in its metrics. It takes into account the topography, waves, storm surges, sea level change, coastal protection engineering, population density, infrastructure, and ecology; values the importance of socioeconomic factors; can be applied flexibly to a wide range

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of coastal environments and scales; varies in accuracy depending on the input data; and does not require numerical simulation (Narra, 2017). The method has been successfully applied to coastal erosion risk assessments in Portugal, Mozambique, and Mexico, providing a more reasonable classification (Narra et al., 2017, 2019a; Narra, 2018; Ferreira et al., 2021). However, its applicability to environments other than China and sandy shores needs to be studied.

Hainan Island is surrounded by the sea, and its main shoreline type is sandy shoreline, which is the most unstable shoreline as it is highly susceptible to erosion. Yang et al. (2010) demonstrated that coastal erosion on Hainan Island has become increasingly prominent in recent decades, with approximately 79% of the coast suffering from erosion, 82% of which is sandy coast. As an international tourist island, Hainan Island is particularly renowned for its high-quality beach resources. However, coastal erosion has left some tourist hotspot beaches facing reduced sand, muddied beaches, narrower and steeper beaches, etc. The tourist environment has been damaged to some extent. Therefore, a risk assessment of coastal erosion on Hainan Island is required to better discuss its influencing factors and coastal protection countermeasures. Currently, studies on the multi-factor coastal erosion risk and vulnerability of Hainan Island are limited. Some researchers have analyzed the status, causes, and prevention measures of typical coastline erosion on Hainan Island. For instance, Wang et al. (2017) evaluated the vulnerability of coastal areas around Hainan Island based on anthropogenic activities (primarily urbanization levels) and natural processes (submarine sediment transport and suspended sediment concentration). Shi et al. (2018) conducted coastal erosion monitoring on seven typical eroded shore sections, including the east coast of Haikou, Longwan Port and Boao coast, Sanya Bay and Yalong Bay coast of Sanya. In this study, a preliminary analysis of coastal erosion risk on Hainan Island in terms of topography and geomorphology, coastal marine dynamics, and socio-economic factors was conducted using the CERA method based on literature, official data, and field surveys, and the influencing factors of coastal erosion and coastal protection countermeasures were discussed. This study aims to find an effective path for comprehensive protection and utilization planning, disaster prevention and safety, and sustainable development of Hainan Island's coastal zone, so as to help decision makers make long-term plans.

## 2 Materials and methods

### 2.1 Study area

Hainan Island is located at 18°10'–20°10'N, 108°37'–111°03'E. The outline of the island resembles an oval pear, with a 290 km long and 180 km wide axis running from northwest to southeast. The province covers an area of  $3.5 \times 10^4$  km<sup>2</sup> on land and  $200 \times 10^4$  km<sup>2</sup> at sea. Most of the rivers originate in the central mountains, forming a radial water system, and the terrain of the province is high in the middle and low in the surroundings with well-developed water systems. The three major rivers of Hainan Island, the Nandu River, Changhua River, and Wanquan River, cover a watershed area of more than 3 000 km<sup>2</sup>, accounting for 47% of the island's area. Hainan Island is surrounded on all sides by sea, and the wave direction is basically north-south, with north-oriented waves dominating in the north and south-oriented waves in the east and south. In Qiongxi, west-south and north are the most common wave directions (Li et al., 2018). The annual aver-

age wave height in the east of the island is approximately 1 m, 0.3–0.5 m in the south, and 0.6–0.7 m along the rest of the coast. From east to west, Hainan Island has three types of tides: irregular semi-diurnal tide, irregular diurnal tide, and normal diurnal tide. The coastal tidal range is relatively small in the east and south, with an average tidal range of 1.0–1.3 m, whereas it is the largest in the northwest, with an average tidal range of 1.5–2.0 m (Bao, 2014).

Hainan Island has a total length of 1 528 km of mainland coastline, with several artificial islands built, mainly in the north and south. Since 1990, the coastline development in Hainan Province experienced a process from farming reclamation to port construction and reclamation construction. The length of artificial coastline increased significantly, while the length of natural coastline decreased, and local sandy coastline suffered serious erosion and functional degradation (Hong and Sun, 2021). Coastal erosion causes coastal collapse, loss of large land resources and mudflats, damage and retreat of natural sea defences, etc., often occur along the coast of Hainan Island. The east coast of Haikou, Jinxin corner of Wenchang, Wanquan River Port section of Qionghai and Yalong Bay of Sanya are seriously eroded, with large average erosion retreat distances (Shi et al., 2018). Sea level has risen about 20 cm in the past century, and the rate of sea level rise will continue to increase in the future, which will aggravate the degree of coastal erosion together with the impact of unreasonable human development and utilization on the coast. The study area conditions and beach information are shown in Fig. 1.

### 2.2 Data sources and analytical method

The coastal zone survey range in this study was 10 km from the coastline in the landward direction and seaward to the 20 m isobath. The risk assessment of coastal erosion risk on Hainan Island was performed using the CERA method, which is based on the Source-Pathway-Receptor-Consequence (SPRC) conceptual model. The source of hazard is wave-climate activity (waves, storms and sea level rise) that can cause erosion; the pathway is the distance from the study area to the coastline. It mainly acts on land and people as a result of land loss due to coastal erosion (Narra et al., 2017, 2019a; Narra, 2018; Ferreira et al., 2021). Therefore, geomorphology and coastal protection works are used to represent the sensitivity of the coast, population density, infrastructure and ecological zoning are used to represent the socio-economic-ecological situation of Hainan Island, storm surge, topography and shoreline distance are used to assess the exposure, and the number of storms, significant wave height, rate of shoreline change and sea level change are used to assess the erosion drivers. The specific index system and information are shown in Table 1. From Table 1, we have described structural framework of CERA method, divided 4 key modules and 12 impact factors, and introduced the source, precision and time of data set, and also the calculation formulas. The data reflect the changes of Hainan Island coast from 2010 to 2020.

Table 2 shows the risk classes corresponding to the characteristics of each indicator. This paper classifies the coastal erosion risk of Hainan Island according to the index characteristics, so as to discuss the coastal mitigation strategy capability of different erosion types. The risk assessment process for coastal erosion is as follows.

(1) Coastal sensitivity, i.e., the tendency of the coast to erode when subjected to high-energy waves, was assessed by Geo and

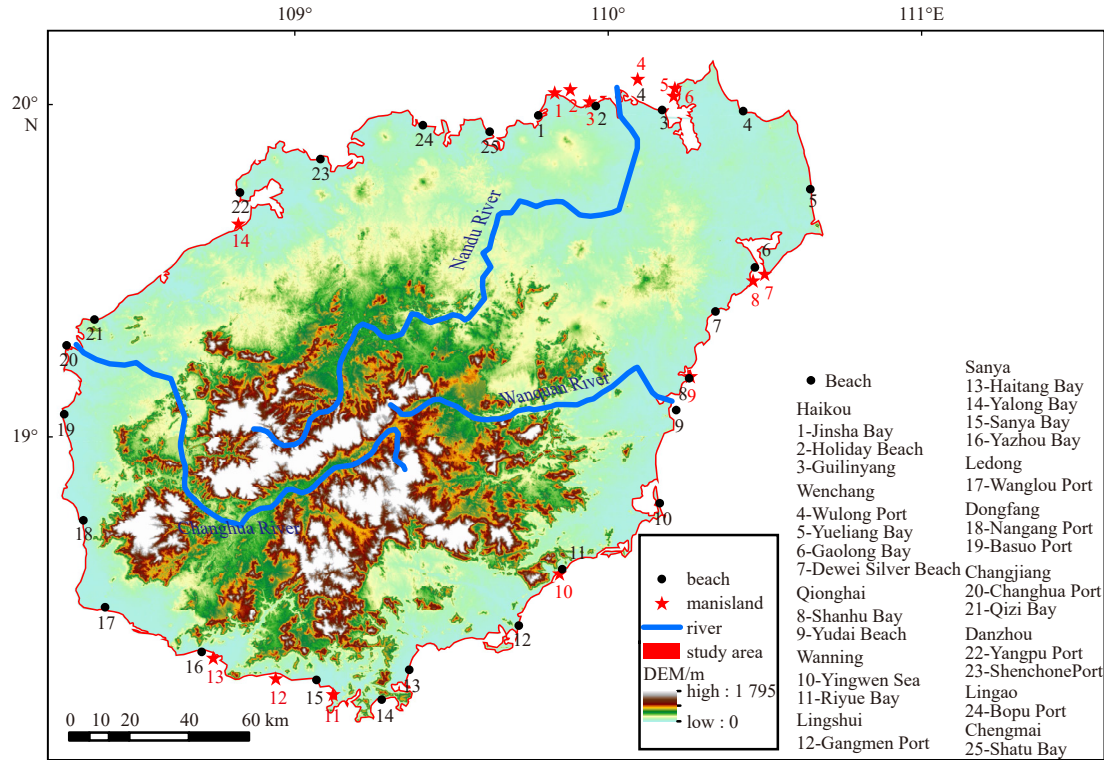


Fig. 1. Locations of the study beaches. DEM: Digital Elevation Model.

Table 1. Index factor information of coastal erosion risk and its data sources, calculation formulas

Module	Indicator	Data source	Time	Formulas
Susceptibility	Geomorphology, Geo	datasets (Alder, 2003; Liu et al., 2020; Chen et al., 2017), field investigation	2020	Susceptibility = int(Geo - Cd) (1)
	Coastal defences, Cd	Google Earth, previous literature	2010-2020	
Value	Population density/(hub-km <sup>-2</sup> ), Pop	Hainan Statistical Yearbook	2020	Value = int(PopInf + Eco) (3)
	Infrastructures, Inf	Open Street Map	2020	
	Ecology, Eco	the Current Situation Map of Marine Space Resources Utilization (Guangzhou Marine Geological Survey)	2015	
Exposure	Storm surge/m, Ss	Bulletin on Marine Disasters in China	2020	Exposure = int(√Dsl × (TopSs) + 0.055) (4)
	Topography/m, Top	ASTER GDEM	2010, 30 m precision	
Coastal erosion	Distance to shoreline/m, Dsl	Google Earth, multiple buffers tool	coastline in 2020 as the baseline	Wc = int(√Hs × Storms + 0.055) (5)
	No. of storms, Storms	the typhoon network statistics of the Central Weather Bureau	2021	
	Significant wave height/m, Hs	European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) hourly data	2020	ScrWc = int(√Scr × Wc + 0.055) (6)
	Shoreline change rate/(m·a <sup>-1</sup> ), Scr	Google Earth, field investigation, DSAS tool	2010-2020, <5 m precision	
Sea level trend/(mm·a <sup>-1</sup> ), Slt	Sea Level Change Bulletin	2020	Coastal erosion = int(ScrWc + 0.1 × Slt) (7)	

Cd (Eq. (1)) Based on geomorphic characteristics and geological composition of Hainan Island's nearshore, Geo was classified from 1 to 5, and a qualitative analysis of coastal erosion resistance was conducted. The sensitivity is low for fiord and rock coast, medium for biogenic coasts such as saltmarsh, mangroves and coral reefs, and high for deltas, exposed beaches and mudflats. The existence of Cd forms a barrier to the spread of coastal erosion hazards and has a protective effect on the area near the works, which is negatively correlated with sensitivity. It includes three types of structures: perpendicular, longitudinal, and de-

tached structures (Fig. 2). The longitudinal attached structure is -2, the perpendicular updrift and longitudinal detached structure is -1, and the perpendicular downdrift structure is 1.

(2) The value of the study area was determined by socio-economic and environmental factors, such as Inf, Pop, and Eco, to assess the value of Hainan Island's coast. According to the socio-economic importance and characteristics of Hainan Province, indicators were classified into classes 1 to 5. The area with higher population density, better infrastructure and higher ecological class has higher value and higher risk loss. To compensate for the

**Table 2.** Characteristic class of each indicator

Indicator	Characteristic class				
	1	2	3	4	5
Geo	rock coast, fiord, fiard	consolidated sedimentary, cliffed, indented coast	saltmarsh, coral reefs, mangroves	pebble/pocket beach, beach with significant dune	barrier system, exposed sand beach, mudflat, deltas
Pop	[0; 500)	[500; 1 000)	[1 000; 2 000)	[2 000; 4 000)	[4 000; +∞)
Inf	no structures	rural agglomeration	urban agglomeration	city centres, main highways	critical infrastructures
Eco	moderate	high	-	-	-
Ss	[0,1)	[1.0,2.0)	[2.0,3.0)	[3.0,4.0)	[4.0,+∞)
Top	[30 + Ss,+∞)	[20 + Ss,30 + Ss)	[10 + Ss,20 + Ss)	[5 + Ss,10 + Ss)	[0,5 + Ss)
Dsl	(350,+∞]	(225,350]	(125,225]	(50,125]	(0,50]
Storms	No	1 to 5	6 to 10	11 to 15	>15
Scr	[+0.5,+∞)	[-0.5,+0.5)	[-1.5,-0.5)	[-2.5,-1.5)	[-∞,-2.5)
Hs	[0,0.4)	[0.4,0.8)	[0.8,1.6)	[1.6,2.0)	[2.0,+∞)
Slr	[-∞,0)	[0.0,1.0)	[1.0,1.8)	[1.8,3.0)	[3.0,+∞)

Note: - represents no data.



**Fig. 2.** Schematic diagram of coastal defences. Longitudinal structure (a), perpendicular structure (b), detached structure (c).

less accurate data for any of the individual indicators, PopInf was obtained by combining the effects of Pop and Inf according to Eq. (2). In the CERA2.0 method, the geometric mean and the constant 0.055 are often used for the combination of two indicators, and the values are then calculated according to Eq. (3). The constant 0.055 can better balance the output by rounding off some combinations of results that are close to the next classification.

(3) Coastal exposure was assessed by Dsl, Top, and Ss to quantify the elements that may be affected by hazards within a certain range (Eq. (4)). Each parameter was divided into classes 1 to 5 according to the numerical interval in Table 2. The closer to the shoreline, the flatter the terrain, and the higher the storm surge, the greater the exposure of the coast. The Ss class was added to the Top class to obtain the variable TopSs. The coastline in 2020 was then used as the baseline, and multiple buffers were made landward to divide Hainan Island into five circular areas. Exposure of Hainan Island's coast is quantified by Eq. (4).

(4) The driving sources of coastal erosion were assessed by Hs, Storms, Scr, and Slr. Coastal erosion risk is positively correlated with these indicators. The variable wave climate (Wc) is obtained by combining the effects of Hs and Storms by Eq. (5) to measure the wave energy and its sediment transport capacity. On this basis, the variable ScrWc is obtained by adding the Scr, which reflects the coastal changes of Hainan Island from 2010 to 2020 (Eq. (6)). Finally, the driving force of coastal erosion is quantified by Eq. (7), and the effect of sea level rise in the short term is small, with a coefficient of 0.1.

(5) Based on the sensitivity, value, exposure and erosion driver data of Hainan Island coast obtained above, the vulnerab-

ility, consequences and risks of coastal erosion in Hainan Island were calculated by using Eqs (8)–(10), classified into 1–5 classes (Narra et al., 2017, 2019a). Vulnerability refers to the amount of potential damage caused by coastal erosion and depends on the sensitivity and value of the coastal area (Eq. (8)). Consequences are impacts, quantifying the potential damage, resulting from a combination of exposure and vulnerability (Eq. (9)). Risk is the combination of the probability of an event and its negative consequences and is a function of sensitivity, exposure, and vulnerability (Eq. (10)).

$$\text{Vulnerability} = \text{int}(\sqrt{\text{Susceptibility} \times \text{Value}} + 0.055), \quad (8)$$

$$\text{Consequence} = \text{int}(\sqrt{\text{Exposure} \times \text{Vulnerability}} + 0.055), \quad (9)$$

$$\text{Risk} = \text{int}(\sqrt{\text{Coastal Erosion} \times \text{Consequence}} + 0.055). \quad (10)$$

(6) To further study the status and influencing factors of coastal erosion on Hainan Island, geomorphological and topographic surveys as well as sediment sampling were conducted on 25 beaches that were evenly selected from July 29 to August 4, 2021. Among them, a total station was used to determine the length and elevation of the profile by observing the vertical direction of the coast to the deepest wading water. Combined with the tide information to determine the range of the supratidal, intertidal, and subtidal zones of the beach, the sediment was collected in each tidal zone, pre-treated, and the content of each com-

ponent of the sediment was obtained by a Sieve Shaker to calculate the mean grain size.

### 3 Results

#### 3.1 Characteristics of indicators

According to the CERA2.0 method, twelve indicators are graded to represent the coastal situation and disaster-bearing capacity of Hainan Island. Table 3 shows the percentage of each class, and Fig. 3 shows the distribution.

The sensitivity module considers Geo and Cd. The landform type of Hainan Island is mainly open beaches and deltas that account for 78.48% of Hainan Island’s landforms, which are highly sensitive to coastal erosion, followed by coral reefs, mangroves (18%), and a large number of small bays. Figure 1 shows the distribution of fourteen artificial islands on Hainan Island built after 2000. The majority are detached structures parallel to the shoreline, with the exception of Yalin Bay and Tanmen Port, which are connected to the coast, and Phoenix Island, which is a detached structure perpendicular to the shoreline and may create erosion hotspots. In addition to artificial island construction, many shore sections are built with hard revetments, breakwaters, and fishing harbor engineering, all of which reduce the sensitivity to coastal erosion.

The value module considers Pop, Inf, and ecological zoning. In Hainan, 78.83% of cities have a Pop of less than 500 people/km<sup>2</sup>. In 2020, the Pop of Haikou was 918 people/km<sup>2</sup> and that of Sanya was 540 people/km<sup>2</sup>. Therefore, the number of affected people was small, and the value was low. The coastline is widely distributed within 10 km landward of urban agglomeration, road networks, and other infrastructure, and the value of the affected area is high. Ecological zoning only has classes 0, 1, and 2. The value of hazards was high from the perspective of ecological zoning because tourism, recreation areas, and marine protected areas account for approximately 88.86% of the Hainan coast, while the shallow sea distribution of agricultural, fishery, and reserved areas, as well as ports and industrial town areas account for a relatively small percentage.

The exposure module considers Ss, Top, and Dsl. The Ss in the coastal zone of Hainan Island is approximately 2 m with a low exposure level. Elevation is more evenly distributed between 0 m and 30 m, and lower elevation areas are more susceptible to coastal hazards. Since the distance from the shoreline to the land as a buffer zone gradually increases, the coastal exposure is small, with only 2.09% of the area in the high-class.

The coastal erosion module considers storms, Scr, Hs, and sea level rise. Hainan Island is surrounded by the sea and significantly influenced by the ocean and typhoons. In 2021, five cyclone activities passed through Hainan, including more transit typhoons in Dongfang, Wanning, Ledong, Lingshui, Wenchang, and Qionghai. The shoreline is considerably changing, showing moderate costal erosion features, with approximately 51.62% of beach sections showing siltation rates greater than 0.5 m/a, and 41.26 % had erosion rates of 1.5–2.5 m/a, 7.11% showed no visible changes. Hs ranged from 0.4 m to 2 m, with medium-high wave heights affecting 85.78% of the area. From 1980 to 2020, sea level rise in the South China Sea was approximately 3.5 mm/a, with a high coastal erosion risk class.

#### 3.2 Results of modules

To classify the coastal erosion risk in the study area, the four modules of sensitivity, value, exposure, and coastal erosion were combined based on the above twelve indicators. The percentage and distribution of the classes of each module are shown in Table 4 and Fig. 4, and the distribution of the indicator composition is shown in Fig. 3.

The sensitivity module assessed the area from the coastline of Hainan to the 20 m isobath (Fig. 4a). The sensitivity of the coastal erosion of 79.22% of the study area was high and was primarily influenced by geomorphic environment (Fig. 3a). Coral reefs and mangroves are extensively spread in Wenchang, Qionghai, Changjiang, and Danzhou, providing a wave barrier effect, and the bay area is sheltered and less sensitive. Cd structures (Fig. 3b), which have an attenuating effect on sensitivity, are mainly distributed in the south and north, particularly in Haikou, Chengmai, Lingao, Danzhou, and Sanya.

The value module assessed the value of the 20 m isobath to the 10 km area from coastline to land (Fig. 4b). Urban centers, important areas of human activity, and ecological protection zones are high-value places and account for 51.01% of the areas, whereas the northeastern part of Hainan Province has a comparatively low value due to its infrastructure type. The shallow sea area accounts for 41.24% of the area and is of low value (Figs 3c–e).

The exposure module assessed the coastline to 10 km onshore (Fig. 4c). With the increase of Dsl, the low exposure accounted for 97.05% of the area and was mainly distributed in the high altitude area (Fig. 3f). The lagoons in the southwest of Sanya and Wenchang were moderately exposed, accounting for 2.55%. Areas with high exposure were scattered sporadically, accounting for only 0.41%.

**Table 3.** Percentage of indicator classes in Hainan

Module	Indicator	Percentage of characteristic classes/%					
		0	1	2	3	4	5
Susceptibility	Geo	-	0.80	2.73	18.00	-	78.48
Value	Pop	-	78.83	21.17	-	-	-
	Inf	-	-	-	14.56	85.44	-
	Eco	1.58	9.56	88.86	-	-	-
Exposure	Ss	-	-	100	-	-	-
	Top	-	26.25	18.30	19.90	22.24	13.32
	Dsl	-	94.79	1.68	1.44	1.18	0.91
Coastal erosion	Storms	-	-	100	-	-	-
	Scr	-	51.62	7.11	14.22	11.29	15.75
	Hs	-	-	14.22	38.49	25.85	21.44
	SlT	-	-	-	-	-	100

Note: A total of twelve indicators are used. Eleven variables are listed above in terms of the percentage of classes in Hainan, and coastal defences cannot be quantified. - represents no data.

The coastal erosion module assessed the coastline to 500 m onshore (Fig. 4d). The number of Ss was small, and coastal erosion on Hainan Island was mainly low class, accounting for 62.21% of the area. The high class only accounted for only 6.87% and was sporadically distributed in Haikou, Wenchang, Qionghai, Wanning and Sanya. The differences between the classification results were mainly related to Scr and Hs, such as higher coastal erosion rates in northern Wenchang, Qionghai and Wanning, and larger wave heights in Haikou, Sanya, Wanning, Qionghai and Wenchang (Figs 3g-i).

**3.3 Results of coastal erosion risk**

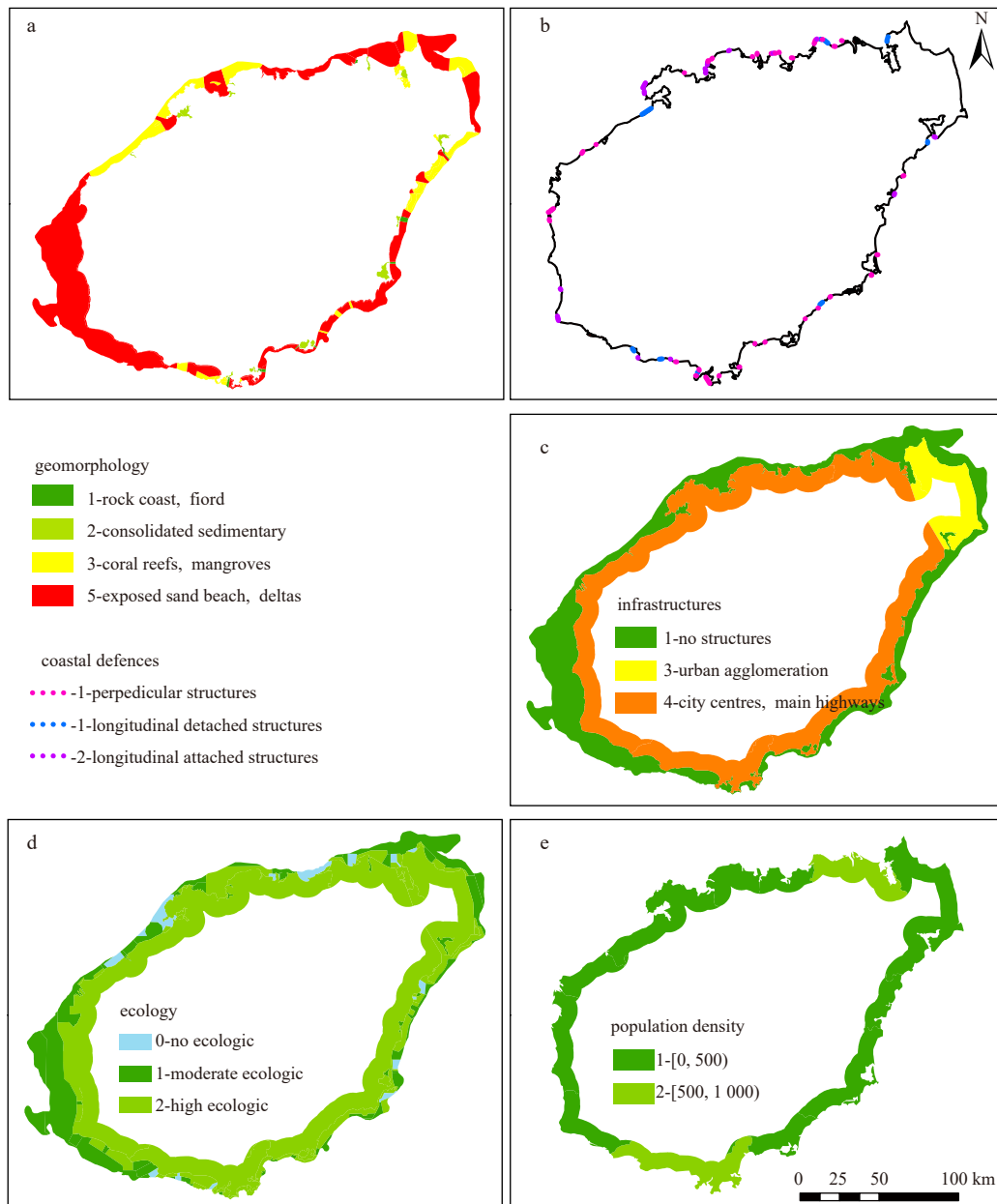
The percentage and distribution results of coastal erosion risk classes in Hainan Island are shown in Table 5 and Fig. 5.

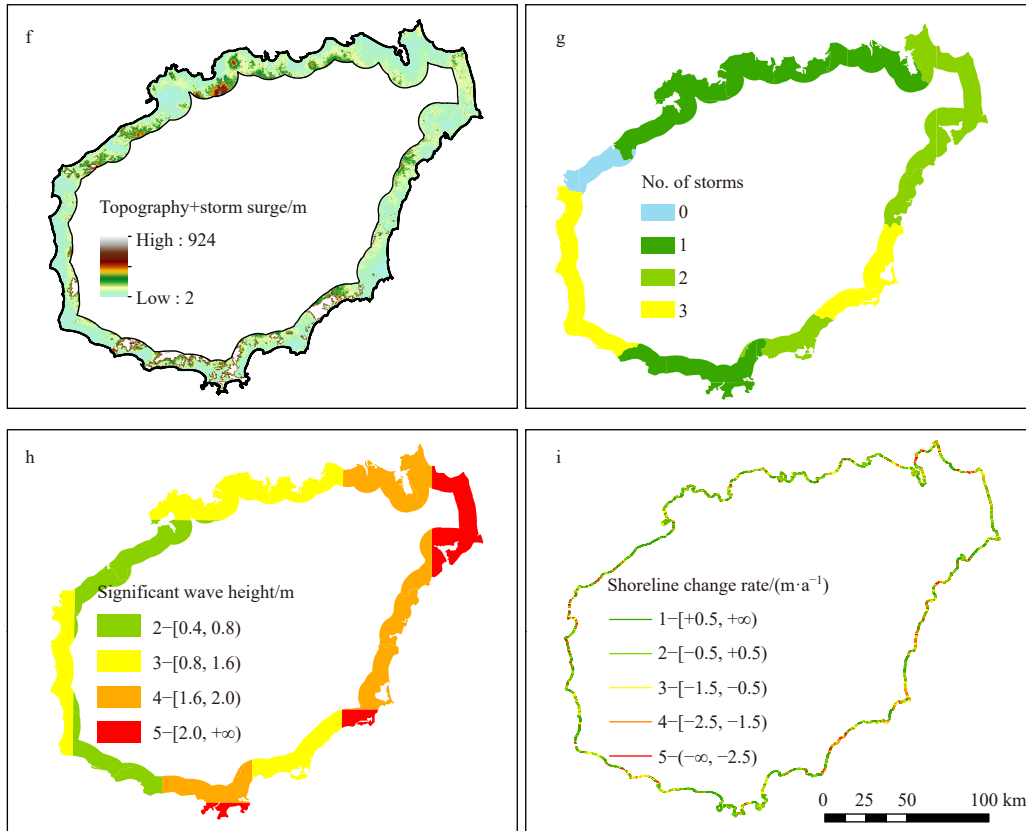
Hainan Island shows high vulnerability and strong spatial continuity, with 59.70% of the area showing a high-class coastal erosion risk and a high potential impact of coastal erosion on the land. Figure 5a shows that areas with moderate vulnerability are

mainly distributed in the northeast and northwest, particularly Wenchang, Changjiang, Danzhou, and Lingao, accounting for 33.82% of the area. There were no extremely high-class vulnerability areas.

The consequence map in Fig. 5b was used to identify the areas that are most likely to suffer from coastal erosion. The high-class loss areas were sporadically distributed in Haikou, accounting for only 4.02% of the area. The consequences for Holiday Beach in Haikou, Gaolong Bay-Dewei Silver Beach in southeastern Wenchang, Yazhou Bay in western Sanya, Yangpu Port in Danzhou, and Shatu Bay in Chengmai were moderate, accounting for 16.67% of the area. In conclusion, 79.31% of the whole island showed low-class losses.

The risk map (Fig. 5c) shows the results of coastal erosion, vulnerability, and consequences, representing the overall situation of coastal erosion on Hainan Island. The coastal erosion risk on Hainan Island was classified from very low to high (1-4), with low risk accounting for 91.51% of the area. Gaolong Bay-De-





**Fig. 3.** Distribution of indicator characteristics. Geomorphology (a), coastal defences (b), infrastructures (c), ecology (d), population density (e), topography+storm surge (f), number of storms (g), significant wave height (h), and shoreline change rate (i) in Hainan.

**Table 4.** Percentage (%) of classes for each module

Module	1	2	3	4	5
Susceptibility	-	2.93	17.25	0.60	78.62
Value	28.78	12.46	7.75	51.01	-
Exposure	63.99	33.06	2.55	0.29	0.12
Erosion	19.77	42.44	30.91	5.75	1.12

Note: - represents no data.

wei Silver Beach in southeastern Wenchang and Yazhou Bay in western Sanya had medium risk, accounting for 8.41% of the area, while high-risk areas were sporadically distributed in Sanya and Wanning, accounting for only 0.08% of the area.

To better study the distribution and influencing factors of coastal erosion risk in Hainan, the shore section from Haikou clockwise to Sanya was considered as the eastern part, and the shore section from Haikou counterclockwise to Sanya was considered as the western part. Figure 6 presents the percentage of vulnerability, consequence, and risk for the east and west of Hainan Island. The vulnerability and erosion risk in the eastern part of Hainan Island were higher than those in the western part, with medium to high risk mainly distributed in the eastern region and a high percentage of very low risk in the western part. In conclusion, the coast of Hainan Island shows high vulnerability and low erosion risk.

#### 4 Discussion

##### 4.1 Applicability of the CERA method

A Monte Carlo simulation was used for sensitivity analysis to assess the applicability of the CERA 2.0 method on Hainan Is-

land (Kroese, et al., 2014). The maximum, minimum and most likely value of each indicator were determined by combining the characteristic grade of Hainan Island (Table 3). One million samples were randomly generated for each input by typing Eqs (1)-(10). Table 6 shows the variance contribution values of each indicator to the modules and results. The results show that all outputs follow an approximately normal distribution. The main contributing indicators of sensitivity, value, exposure, and coastal erosion modules were Geo, Pop, Dsl, and Scr, each contributing more than 50%. Moreover, Geo type contributed significantly to vulnerability and consequences, with the Scr contributing the most to risk, affecting 55.3% of risk and 71.7% of coastal erosion outcomes. The Pop and number of storms also had a significant impact on risk, with variance contributions of more than 10%. However, the variance contributed by sea level rise was 0. The result could be explained by the fact that CERA2.0 considers its impact to be small in the short term and therefore sets its impact coefficient to 0.1 (Eq. (7)), which may be valid in the short term.

The CERA method has been applied to coastal erosion risk studies in Portugal, Mozambique, and Mexico (Narra, 2018; Narra et al., 2017, 2019a; Ferreira et al., 2021). These areas are long, continuous, low-lying open gravelly coasts with high en-

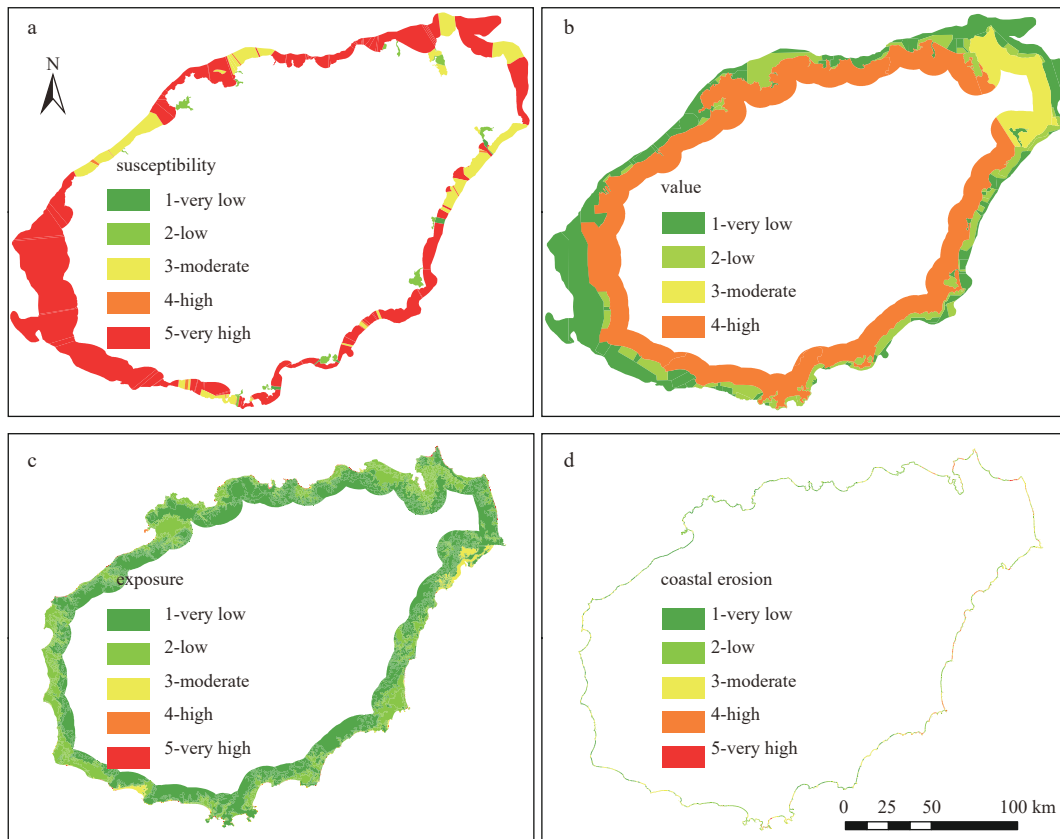


Fig. 4. Distribution of module results. Susceptibility (a), value (b), exposure (c) and coastal erosion (d) module in Hainan.

ergy wave climates, high Pop, Cds, such as breakwaters, or facing problems such as sediment reduction. The coast of Hainan Island has the above characteristics and also has coastal environments other than low-lying sandy shorelines, verifying its applicability to other coastal environments. This study was aimed at estimating the coastal erosion risk on Hainan Island through CERA. The results showed that Haikou, Sanya, Wanning, and Wenchang were high-risk erosion areas, and the shore sections of the east side of Wulong Port, Yalin Bay in Wenchang, and Yalong Bay in Sanya were extremely eroded, which is consistent with previous studies (Shi et al., 2018). Therefore, the CERA method is applicable to the coast of Hainan Island, and the results of the study are reliable and useful in examining the differences in the spatial distribution of erosion risk. However, in the medium and long term, its framework can be further improved, such as by including scenario simulation or using elasticity indicators to develop a more robust value assessment module. The current Pop is calculated using the resident population, and the seasonality of Pop in tourist areas can be taken into account. The influence of sea level rise should be given due consideration and the impact coefficient should be adjusted accordingly. Moreover, the spatial variation of indicators can be fully considered to strengthen the refinement study.

#### 4.2 Main influencing factors of regional differences in erosion risk

##### 4.2.1 Natural factors

The sandy coast and artificial coast constitute the majority of Hainan Island, with the sandy coast accounting for approximately 40% of the total coastal area. Because of the loose structure of sand, it is easily migrated, transported, and deposited under

Table 5. Percentage (%) of coastal erosion risk classes

Result	1	2	3	4
Vulnerability	1.78	4.70	33.82	59.70
Consequence	10.19	69.12	16.67	4.02
Risk	27.28	64.23	8.41	0.08

external dynamic conditions, providing the material basis for coastal erosion (Li et al., 2011). The assessment by the CERA method showed that the risk of coastal erosion is influenced by topography, waves, tides, and other factors, which are determined by the dynamic environment and typhoon conditions of the study area.

##### (1) Typhoons and storm surges

In the northwest Pacific, Hainan Island is one of the most severely affected regions by typhoons, characterized by high frequency, high intensity, wide impact, and long affected seasons. According to the Central Weather Bureau, a total of 268 tropical cyclone activities hit Hainan Island between 1949 and 2021, including about 2–3 tropical storms per year. Typhoons can cause dramatic changes in hydrodynamic conditions, sediment dynamics processes, and coastal ecosystems when passing through or landing on the coastal zone, which are the main natural factors that exacerbate coastal erosion. The two processes, storm surge and waves, coexist and interact at the nearshore, and their impact on coastal erosion is mainly in the form of offshore sand transport. The coastal water gain forms a strong vertical circulation or erosive rift current, which carries the sediment lifted by waves and its own eroded bottom sand to a depth far offshore to accumulate or be carried away by the tide. Instantaneous erosion during storms is an important phenomenon, and the impact of storm surges can be quantified by sediment volume, shoreline

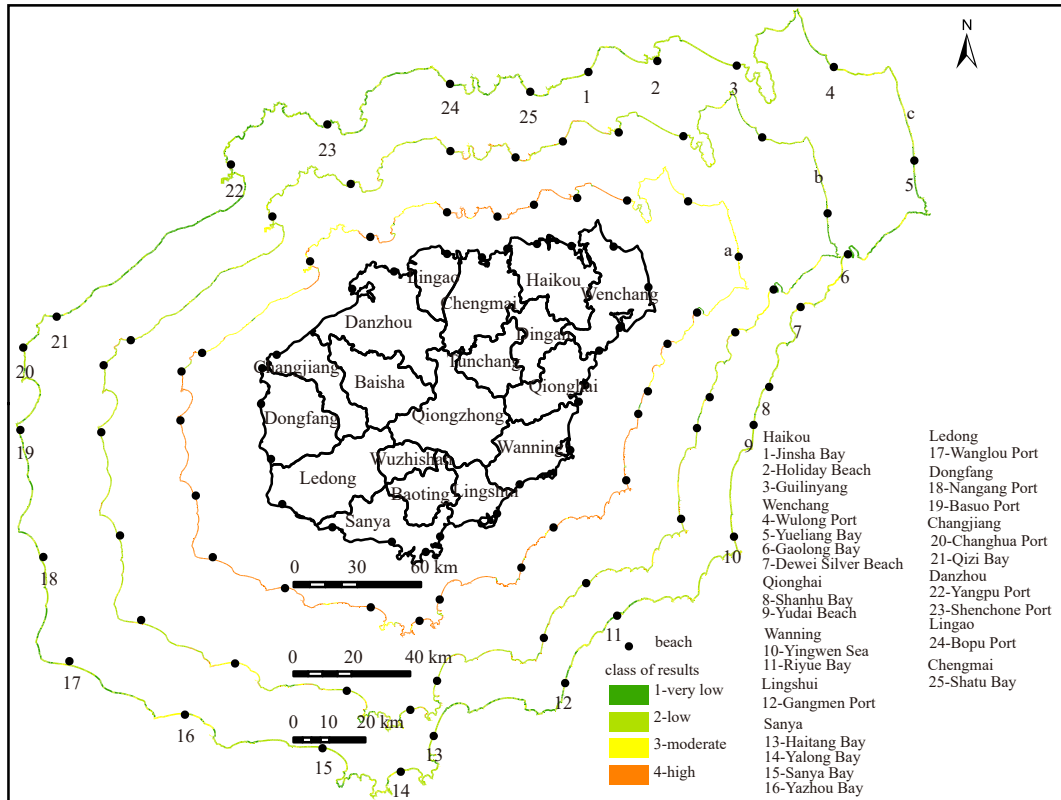


Fig. 5. Results of vulnerability (a), consequence (b) and risk (c) in Hainan.

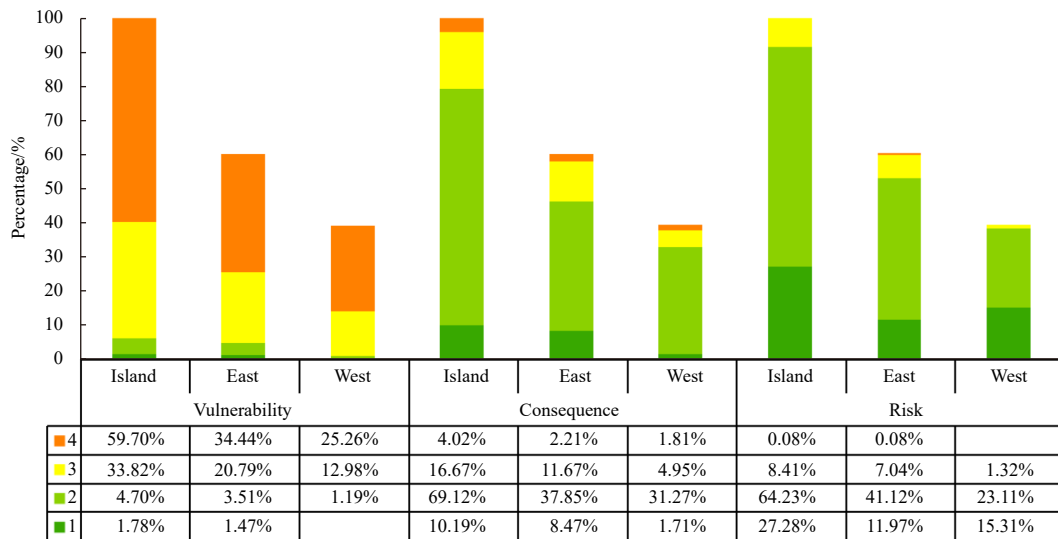


Fig. 6. Percentage of each class of vulnerability, consequence and risk in Hainan.

Table 6. Monte Carlo simulation of CERA2.0, shows the variance contribution values of each indicator

	Geo	Cd	Inf	Pop	Eco	Dsl	TopSs	Hs	Storms	Scr
Susceptibility	94.9	5.1	-	-	-	-	-	-	-	-
Value	-	-	25	55.2	19.8	-	-	-	-	-
Exposure	-	-	-	-	-	74.8	25.2	-	-	-
Erosion	-	-	-	-	-	-	-	12.1	16.2	71.7
Vulnerability	63.6	2.9	8.8	16	8.7	-	-	-	-	-
Consequence	39.7	1.8	4.7	7.7	5	30.1	11	-	-	-
Risk	-	-	6.1	13	3.7	-	-	9.3	12.5	55.3

Note: - represents no data.

distance before and after storms, or maximum shoreline retreat distance (Callaghan et al., 2009; Audère and Robin, 2021). Sometimes, the amount of erosion caused by strong storms exceeds that of a full year of normal weather (Xu et al., 2013). Hu et al. (2022) studied the impact of the 16th Storm Bebege on Qing'an Bay, north coast of Qiongzhou Strait in 2018 and found that beach erosion of up to 5–6 m before and after the storm.

(2) Sea level rise

Sea level rise is a common cause of coastal erosion development in China and globally, and its long-term, potential, and cumulative nature causes coastal retreat that cannot be ignored (Ji, 1996). In 2020, Hainan coastal sea level was 65 mm higher than normal, with seasonal high sea level period from September to November. The IPCC's 5th Assessment Report (AR5) was used to identify climate scenarios according to the Representative Concentration Pathway (RCP), with RCP4.5 representing a medium emission scenario and RCP8.5 representing a high emission scenario. Table 7 shows the mean sea level rise values under the corresponding scenarios. Under the RCP4.5 scenario, global sea level rise is expected to be 0.26 m in the middle of the 21st century, and 0.49 m by the end of the century. Sea level changes are more pronounced under the RCP8.5 scenario, posing serious challenges to human survival and development in coastal areas.

Bruun (1962) first proposed the idea of increased coastal erosion due to sea level rise, arguing that as sea level rises, the equilibrium profile of the beach will remain in place and shift upward toward the shore, with the shore retreating and eroded material accumulating in the lower part of the beach, and the coastal wave energy and propagation speed would be significantly strengthened (Li et al., 2011). The relationship between the value of sea level rise ( $a$ ) and the distance of coastal retreat ( $S$ ) is given by

$$a = (h/L) \times S, \tag{11}$$

where  $h$  is the height of the beach profile and  $L$  is the length of the profile derived from the measured data. The smaller the coastal slope, the greater the influence of sea level change and the distance of shoreline retreat. The slope of each beach and the coastal retreat distances under each scenario are shown in Fig. 7.

The slope of the study beaches ranged from 2.2% to 12.5%, with slopes exceeding 10% at Yingwen Sea, Wanglou Port, and Bopu Port, resulting in smaller coastal retreat distances. The re-

treat distance in the mid-21st century were similar under the RCP4.5 and RCP8.5 scenarios, ranging from 2.0 m to 14.0 m for each beach. At the end of the 21st century, the retreat distance increased more under the RCP8.5 scenario than under the RCP4.5 scenario. The retreat distance of Gaolong Bay was the largest and that of Wanglou Port was the smallest. The retreat distance in the east was larger than that in the west, which was more strongly influenced by tidal dynamics. According to the above, the coastal sea level rise in the South China Sea from 1980 to 2020 was 3.5 mm/a, reaching the highest class in the CERA model, and from 2010 to 2020 it was 1.5–2.5 mm/a, accounting for 41% of the shoreline erosion rate in Hainan Island. If no precautions are taken, the effects of sea level rise will continue to intensify, and the distance of coastal retreat will increase exponentially by the end of this century. According to the RCP8.5 scenario, the coast will recede by 5.6–31.0 m and a significant amount of land resources will be lost, especially in high emission areas (RCP8.5 scenario).

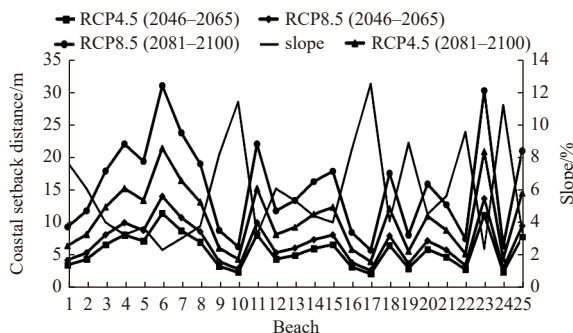
(3) Sediment grain size

The equation of equal moment method by Collias et al. (1963) was used to calculate the mean grain size of Hainan Island beaches in this study (Fig. 8). The mean grain size visually reflects the combination of sediment thickness and size, indicating the average dynamic size of sediment transport. The mean grain size of sediments on each beach of Hainan Island ranged from  $\Phi = 0$  to  $\Phi = 3.1$ , with smaller ones near the lagoon,  $< \Phi = 1$ , and coarser grains, such as beaches 9, 10, 12, and 20. The most common types of sand are very coarse, coarse, medium, fine, and very fine. The sediments in Danzhou, Lingao, Chengmai, Haikou, and Wenchang were mainly of the fine sand type, while the sediments in other areas were relatively coarse. And the sediments in the coastal erosion high-risk areas of Hainan Island were mainly fine and medium sands with a larger mean grain size because fine sands have less barrier effect on coastal erosion than coarser sands, increasing the risk of coastal erosion.

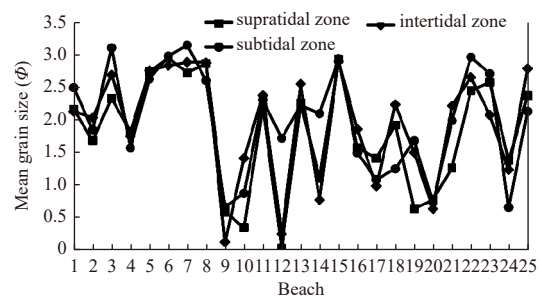
The grain size distribution of sediments indicates the wave energy size, sediment source, and movement path, providing supporting evidence for coastal erosion studies. Sediment grain size is related to the wave energy size, the higher the wave energy, the coarser the sediment grain size left behind. Under the action of wave shallow water deformation and breaking waves, the sediment grain size is larger in the upper part of the beach and smaller in the lower part. The beaches with this characteristic are

**Table 7.** Climate scenarios and global mean sea level (MSL)

Scenarios	RCP4.5 (2046–2065)	RCP4.5 (2081–2100)	RCP8.5 (2046–2065)	RCP8.5 (2081–2100)
MSL/m	0.26	0.49	0.32	0.71



**Fig. 7.** Coast retreat distances of each beach under RCP4.5 and RCP8.5 scenarios.



**Fig. 8.** Mean grain size of surface sediments.

mainly distributed near the estuary, headland, and lagoon of Hainan Island. Simultaneously, the coarser particles that are not easily transported tend to concentrate near the sediment source. Several studies have reported that the amount of incoming sediment is the most important factor affecting coastal erosion (Xu et al., 2013; Wang et al., 2017).

#### 4.2.2 Human factors

Several studies along the coast of China have suggested that human activities are the main cause of contemporary coastal erosion (Xia, 1993). According to the assessment by CERA, coastal erosion risk is influenced by anthropogenic factors such as Cd, Eco, Pop, and Inf. Erosion risk is high in areas with high Pop and complete Inf, and Cd can reduce erosion risk in the short term. The eastern and southern parts of Hainan are affected by artificial structures, resulting in local erosion, while the northern part of the Nandu River is affected by sand dredging from upstream, resulting in reduced incoming sediment and erosion. In addition, coral reef mining, mangrove destruction, and irrational coastal construction can also lead to erosion.

Hainan Island is built with more artificial islands and fishing harbor engineering than seawalls. Seawalls and revetments keep the shoreline from receding by isolating marine dynamics from the land, which can achieve the goal of stabilizing the shoreline in a specific time and location. However, in the long run, it will intensify beach erosion and destruction, leading to beach degradation. The construction of fishing harbors commonly uses natural headlands and islands to form bay-au and extends the construction of breakwaters of different angles and scales to block wind and waves, which affects the hydrodynamic conditions, thus indirectly destroying the balance of sand transport along the coast and causing erosion and siltation of beaches (Li et al., 2019). Artificial islands are one of the important ways of reclamation. Since 2000, up to fourteen artificial islands have been approved for construction in Hainan Province. Artificial island construction will alter the flow field in the area surrounding the engineering, disrupting the original state of marine dynamic equilibrium and causing many problems. The impact on sandy coast and near-shore sea area is particularly considerable as the beach shows significant back-island siltation and erosion characteristics on both sides.

#### 4.3 Coping strategies on coastal erosion

Coastal erosion is a natural hazard that cannot be completely eliminated, but scientific measures can be taken to minimize it. In order to take appropriate measures, it is necessary to identify the erosion causes of each erosion section and improve the knowledge of hydrodynamic factors and sediment transport laws. Further, coastal protection measures such as groins, offshore dikes, shore protection, beach sand replenishment, and biological measures, etc. are scientifically applied. However, the use of hard structures to protect the coast has several drawbacks, such as blocking the upstream incoming sand and causing erosion and beach retreat in the downstream section. Sand replenishment is currently being used to repair damaged beaches on the east side of Sanya Bay, and it is recognized as an environmentally friendly and cost-effective response to coastal erosion (Shi et al., 2015). Biological measures, such as planting spartina, banning coral collection, and protecting and planting mangroves, can effectively restore the ecological balance. Currently, a combination of the above three approaches is often used to protect against beach erosion. Simultaneously, there is a great concern regarding the ability of social-ecological systems to recover after

a disturbance, i.e., the resilience of the system. Resilience is considered a desirable attribute in the face of short-term and long-term stresses (Klein et al., 1998). Therefore, an integrated assessment of ecosystem vulnerability and resilience can help develop adaptation strategies to improve the long-term sustainability of coastal areas.

#### 5 Conclusions

This paper uses the CERA method to assess the vulnerability, consequences and risks of coastal erosion on the coast of Hainan Island, and analyzes the important influencing factors and coastal protection countermeasures for coastal erosion. The following conclusions were obtained.

(1) The coast of Hainan Island is an urban and densely populated area with high value, high sensitivity and moderate erosion, with some attenuating effect of coastal defenses. The whole island showed high vulnerability but low coastal erosion consequences and risk, with the eastern region being more affected by erosion, particularly the eastern side of Wulong Port, Yalin Bay, and the shore section of Yalong Bay, having a very high risk of coastal erosion.

(2) Monte Carlo simulation was used to check the applicability of the CERA method, and it was found that geomorphology, population density, distance to shoreline, and rate of shoreline change were the main contributing indicators of sensitivity, value, exposure, and coastal erosion modules, respectively. Moreover, Geo type contributed significantly to vulnerability and consequences, with the rate of shoreline change contributing the most to risk, and population density and number of storms had a significant impact on risk.

(3) The coastal characteristics and erosion results of Hainan Island were also analyzed, and CERA2.0 was found to be applicable. But there are some improvements. The continuous sea level rise will lead to a gradual increase in coastal retreat distance, especially in high emission areas (RCP8.5 scenario), where the coast will retreat 5.6–31.0 m by the end of the 21st century. Therefore, the impact coefficient should be adjusted to show its importance. Additionally, coarser sediment has a certain blocking effect on coastal erosion. It is suggested that sediment grain size should be included in the index system of coastal erosion risk assessment, and the spatial variation of indicators should be fully considered to strengthen the refinement study. In order to mitigate coastal erosion scientifically, a comprehensive assessment of coastal vulnerability and resilience should be conducted to develop appropriate strategies, in addition to the scientific application of coastal protection works, beach feeding and biological measures.

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