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Assessing the vulnerability of changing coasts, Hainan Island, China

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Abstract

Knowledge of coastline changes and vulnerability is of great importance to local government departments that are responsible for the management and development of coastal zones. To study the nature of change and vulnerability along the coasts of the Hainan Island, we collected a large number of sediment samples through the last few years, and reconstructed the changes of the coastline by combining the data of sediment grain-size analysis and the nautical charts/TM RS imaginary. Contrary to being almost free from erosion (as expected from the findings that the coastlines are in a relatively stable state), four major cities in Hainan (i.e., Haikou, Wenchang, Sanya and Changjiang) turned out to be suffered from a moderate coastal vulnerability primarily because of the large populations that impose considerable pressure on the coastlines. Thus, the assessment methodology utilized in this study, including both anthropogenic and natural factors, serves as a useful tool to obtain a comprehensive understanding of coastline vulnerability for local government, in terms of coastal management and adaptation.

Key words: coastline changes, vulnerability assessment, human and natural factors, Hainan Island

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1 Introduction

Covered by a large and widely distributed area (Eisma, 1998) with a highly increasing population and economic development (Pilkey and Cooper, 2004), coastal zones are subject to the pressure from industry, commerce, residential development and demographic changes (Small et al., 2000), including recreation, extraction of mineral resources and fossil fuels, transportation and navigation, waste disposal, and harvesting of fish, shellfish, and other living marine resources. It is compelling of the effective management, beneficial use, protection and development of coastal zones for human benefits both in the present and the future (Kirwan and Megonigal, 2013), while human's over-exploitation of natural resources in recent years (Dai et al., 2013a, 2014, 2015) has resulted in the loss of ecologically fragile and vulnerable marine resources, wildlife and nutrient-rich coastal areas (Kirwan and Megonigal, 2013). In addition, relative sea level rise is inevitable over coming decades (IPCC, 2007; Feng and Tsimplis, 2014), and this may further threaten coastal zones worldwide. Therefore, an in-depth understanding of coastal changes (i.e., erosion and accretion) and the vulnerability of coasts are essential for management, urban planning, and sustainable decision-making of the coastal zone.

Despite the numerous assessments of shoreline change and vulnerability with various methods, including the extraction of shoreline change information from the historic charts (Yang et al., 2005; Gao et al., 2010; Dai et al., 2013a, 2014, 2015) and the remote sensing images (Kostiuk, 2002; Dai et al., 2013b, 2015), the reliability of these methods are not undisputed. The long-term evolution of beaches is generally the production of a complicated combination of natural factors (e.g., winds, storms, currents and relative sea level rise), and anthropogenic factors (e.g., river dams, biological engineering, land reclamation, and dredging), which are highly variable in different temporal and spatial scales while interactive with each other. As a result, it is not easy to clarify the causes of coastal changes and assess the vulnerability of coastal zones.

Being developed by Gornitz et al. (1994) based on the Coastal Vulnerability Index (CVI), the Beach Vulnerability Index (BVI) has been applied in several studies of beach erosion vulnerability (Abuodha and Woodroffe, 2007; Small et al., 2000; Bird, 1985). The reasons for its widely application include: (1) being apt to rank the vulnerability of beaches easily; (2) being applicable to all beaches; (3) consideration of the predominant hydrological and sedimentary dynamic processes in the beach evolution, includ-

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ing those operating over a long time scale (e.g., a gradual sea level change) and a short time period (e.g., a storm event); and (4) providing a simplified numerical approximation of the principal physical processes that control beach evolution, avoiding calculations that demand high processing capacity. Therefore, the BVI makes it possible to evaluate the vulnerability of coasts and minimize the possible socioeconomic losses caused by natural disasters.

The aim of this study is to analyze the distribution of erosion/accretion coasts and assess the vulnerability of the coastal zone in Hainan Island with an integrated assessment method. This study provides new insights into the vulnerability of beach zones in the Hainan Island, which shall be helpful to local government and coastal management departments.

2 Study area

As the second largest island in China, the Hainan Island is located in the South China Sea (Fig. 1a). It is separated from Guangdong's Leizhou Peninsula to the north by the shallow and narrow Qiongzhou Strait. The island is bounded by the South China Sea continental shelf to the northwest, with its east and south facing the sea, and it is bounded to the west by the Beibu Gulf (Fig. 1b).

The Hainan Island covers an area of 33 907 km^2, and is abundant of ecological, natural, and tourism resources. Among the ten major cities in Hainan Province, the capital Haikou is located on the northern coast of the island and Sanya is a well-known tourism city on the south coast. The other major cities include Wenchang, Qionghai, Wanning, Wuzhishan, Dongfang, and Danzhou. The north Hainan has a humid and subtropical climate whereas the rest part has a tropical monsoon climate. The annual mean temperature is 22.8–25.8°C, with January and February being the coldest months and July and August being the hottest months (Zhang et al., 2013).

Tropical typhoon events occur frequently in summer with an average frequency of 5–10 times per year (Shanghai Typhoon Institute, 2006), accounting for 70% of the annual precipitation (up to 500 mm per event) and the summer rainy season. Major floods accompanying the typhoons could bring problems to local residents. As a contrast, the climate is dominated by north winds in winter (Zhang et al., 2013). The Hainan Island is also known for the disasters related to marine extreme environments, including frequent algae blooms, storm surges and storm waves.

The coast of the Hainan Island includes a variety of geomorphological features: sandy beaches and bars (on the northwest and east coasts), lagoons and estuaries, tidal channels, fringing coral reefs (e.g., the Sanya Coral Reef National Marine Nature Reserve located along the southern coast of Sanya City) and mangroves. The island has an irregular diurnal and semi-diurnal tide. Within the range of less than 55–197 mg/L, suspended sediment concentrations (SSC) are relatively low compared with the Changjiang River and Huanghe River systems in China's mainland.

3 Materials and methods

All surface sediment samples collected from the Hainan coast were deflocculated before sediment grain size analysis to avoid the measurement of any larger flocs. Sediment grain size analysis was performed on a laser particle size analyzer (Malvern Mastersize 2000, UK).

A grain size trend analysis (GSTA) model was used to obtain grain size trends and sediment transport information in preparation to determine net sediment transport pathways in the following step. A 2D GSTA model was utilized to identify the sediment transport pathways in the study area, which was founded by Gao and Collins(1991, 1992) based on the assumption that in the direction of transport, sediment becomes either better sorted, finer and more negatively skewed, or better sorted, coarser and more positively skewed. A grain size trend vector can be defined for two neighboring sites accordingly.

A characteristic distance, D_{cr}, is defined to determine whether or not two sites are neighboring sites: if the sampling distance is smaller (larger) than D_{cr}, the two sites are considered neighboring (not neighboring). Gao and Collins (1992) suggested that the maximum sampling distance between two sites within the concerned area be used as D_{cr} in the GSTA model.

For any site, grain size trend vectors between neighboring sites can be derived using the GSTA model. A resultant vector is then calculated by summing all the vectors. To remove the noise, all the resultant vectors at all sites are smoothed (Gao and Collins, 1992), and the horizontal GSTA vector patterns are used

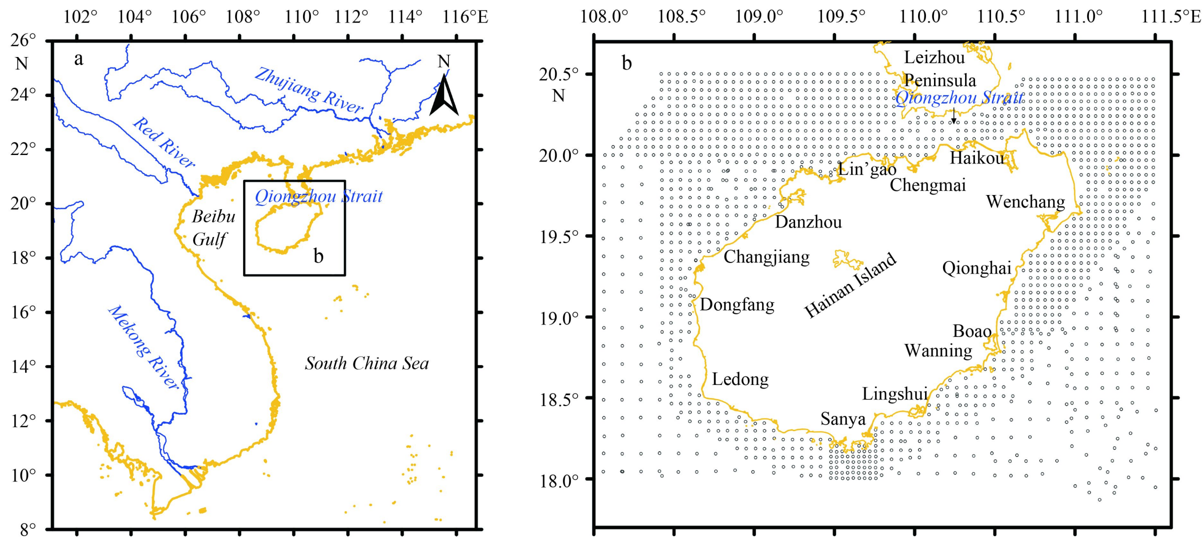

Fig. 1. Location of study area (a), and sediment sampling stations (b) surrounding the coastline of the Hainan Island. The dots in Fig. 1b indicate the seabed sediment sampling stations.

to represent the net sediment transport pathways. For a small sedimentary unit or material transport system, the sampling grid should be dense enough to obtain high-resolution results. Yet, sampling grids that are too dense will lead to additional noise (Gao, 1996). To apply this model to sites that are not evenly distributed, the study area is divided into four sub-areas. Different characteristic spatial sampling intervals are adopted for each part. Grain size trends are obtained by removing the "edge effect".

The coastline derived from the 1990 and 2000 nautical charts coincides well with that from the TM images utilizing GIS software (i.e., Esri ArcGIS).

The coastline vulnerability was assessed in this study with the following classic model:

$$H = (N + H_u + D)/3, \quad (1)$$

where H refers to the coastline vulnerability, N represents a natural factor (including sea level rise, tidal range and coast area), H_u represents a human factor (e.g., the urbanization level), and D represents a dynamic factor (e.g., mean deposition and erosion rates). To assess the vulnerability of the Hainan Island coastline, H was defined as

$$-1.6 < H \leqslant 0 \qquad \text{low vulnerability}, \quad (2)$$

$$-2.4 < H \leqslant -1.6 \qquad \text{moderate vulnerability}, \quad (3)$$

$$H \leqslant -2.4 \qquad \text{high vulnerability}. \quad (4)$$

4 Results

4.1 *Erosion/accretion characteristics*

4.1.1 *Type, composition, and grain size of bottom sediments*

As illustrated in Fig. 2, the grain size of the bottom sediments sampled along the coastline of Hainan Island ranged from 4–63 μm (mud) to 250–2 000 μm (sand). Sediments from the coastlines that are close to the Beibu Gulf and Qiongzhou Strait belong to mud and silty sand, respectively, whereas those from other coastlines around the Hainan Island were a mixture of sandy silt and silt.

Figure 3 displays the proportions of the various classifications of grain-size discovered in the sediment samples from the coastline of Hainan Island. The proportions of clay, silt, sand and gravel along the coastline of Qiongzhou Strait ranged from approximately 0% to 10%, 10% to 20%, 50% to 80% and 0% to 30%, respectively, whereas 0% to 10%, 20% to 50%, 40% to 60%, and 0% to 10% around the Boao coast, implying that sand dominates the sediments deposited along the coastline of Qiongzhou Strait whereas silt and sand collectively dominate along the Boao coastline. The sand content ranged from 30% to 70% along the

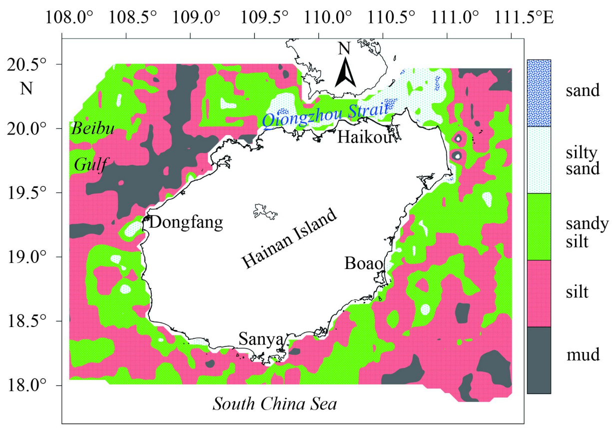

Fig. 2. Distribution of sediment types in the coastline of Hainan Island.

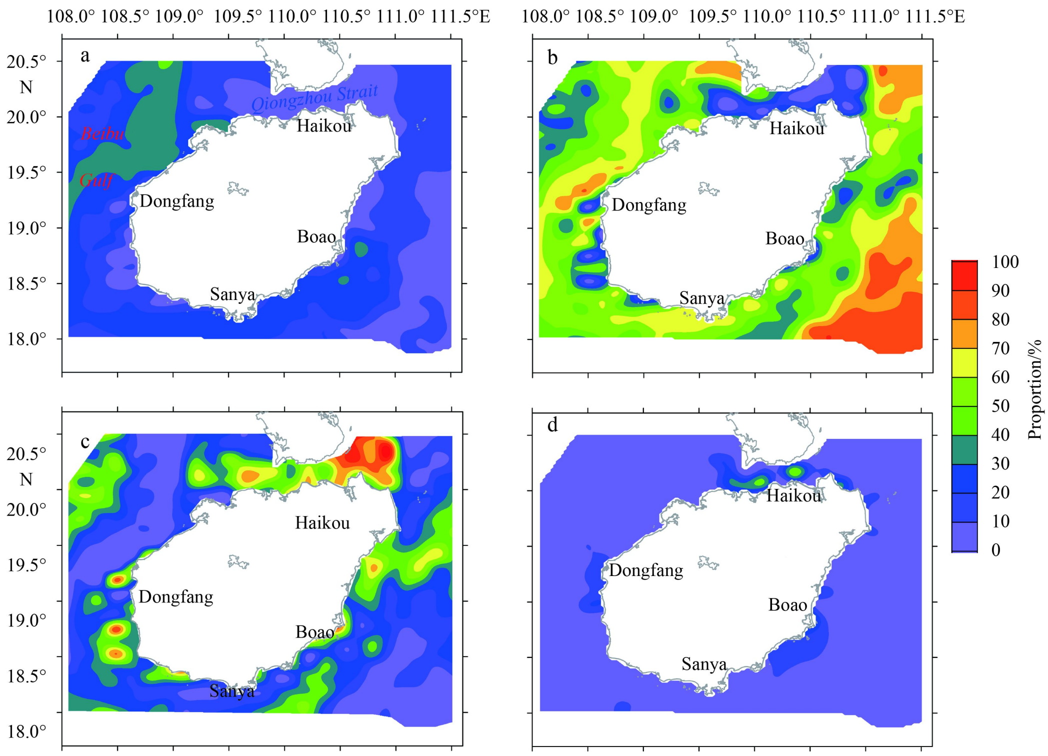

Fig. 3. The proportions of clay (a), silt (b), sand (c), and gravel (d) in the sediment of the coastline of Hainan Island.

coastline between Dongfang and Sanya; yet, sandy silt and silt collectively predominate the sediment along the coastlines of other parts of the Hainan Island.

4.1.2 *Sediment transport trends*

The sediment transport pathways identified with the method of grain size trends analysis (Gao and Collins, 1991, 1992) are illustrated in Fig. 4. There are two sediment transport centers where the deposition is concentrated (denoted as I and II). The sediment transport trend is seaward adjacent to Haikou and Boao while landward close to Sanya and south Dongfang, suggesting that the occurrence of erosion in the coast of Boao and Haikou while accretion close to Sanya and Dongfang.

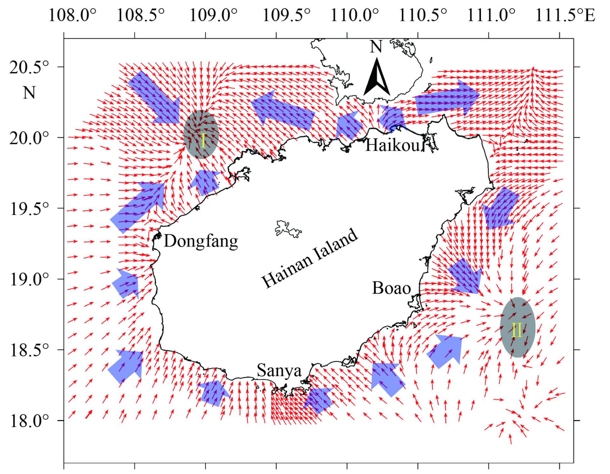

Fig. 4. Sediment transport pathways identified with the methods of grain size trend analysis proposed by Gao and Collins (1991, 1992) as described in Section 3.

4.1.3 *Sedimentation rates and SSC patterns*

Four sites were selected for further analysis: the coastlines of Boao, Sanya, Dongfang, and Beibu Gulf (see Figure 4-2 in Zhang (2011)). The sedimentation rate derived from ^{210}Pb isotopic analysis, up to 32 mm/a, is believed a relatively high value in the given areas, e.g., lagoons and the coastal zone between capes along the western coastline of Hainan Island. By contrast, the sedimentation rate of merely 2 mm/a is supposed low in the open water areas along the south coast. This result is in consistence with the finding that sedimentation rates along the western coastline of Hainan Island are generally higher than those along the eastern coastline (Zhang, 2011).

Xia (2015) surveyed the spatial and temporal distribution of SSC in the coast zone surrounding the Hainan Island, reporting an overall higher trend of SSC towards the west coastline, and a lower trend towards the east coastline. On average, nearshore SSC is higher than offshore value, which implies the arising of sediment resuspension in the nearshore region. Paradoxically, it is not uncommon to discover the maximum SSC of up to 30 mg/L in some coastal waters near ports.

We also obtained the surface SSC distributions by analyzing remote sensing imagery (refer to Zhang (2011) for the results of the synchronous distribution). On average, the lowest value of annual SSC (8 mg/L) around the Hainan Island appears in spring (Zhang, 2011).

4.2 ***The change of coastline surrounding the Hainan Island***

We determined the change of coastline surrounding the Hainan Island based on the erosion rates (Table 1). As illustrated in Fig. 5, the coastlines of Sanya and Lin'gao are in an overall steady state. The west coastline of Sanya, the east coastline of Lin'gao as well as the complete coastlines of Dongfang are characterized by a weak accretion, the Beibu Gulf experienced a heavy acceleration, whereas Wanning coastline suffered an intense erosion. Accretion and erosion appear alternatively with various intensities along the eastern coastline of Hainan Island as a whole.

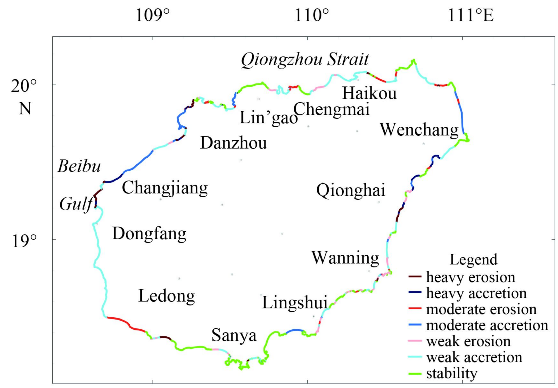

Fig. 5. The change (erosion/accretion) of the coastline surrounding the Hainan Island.

4.3 ***Vulnerability assessment***

Results of the coastal vulnerability assessment are exhibited in Fig. 6, and Tables 1 and 2. As shown in Fig. 6 and Table 2, the four coastal sites (Haikou, Wenchang, Sanya, and Changjiang) were labeled with moderate vulnerability, contrary to the attribution to low vulnerability of all the rest sites, with no one being classified as highly vulnerable site. It is thus suggested that coastal vulnerability is concentrated on the large cities of Hainan Island. Among the great deal of human and natural influencing factors as listed in Table 1, the increasing populations and economic development predominate the coastal vulnerability.

5 Discussion

5.1 ***Factors influencing coastline change***

The change of coastline is influenced complexly by a series of natural and human factors (Dai et al., 2010a, b; Wang et al., 2012; Wei et al., 2014). Natural factors, including waves, tidal currents, weather, sea level rise and local conditions such as coastal vegetation and rivers, exert impacts on the physical, chemical and biological processes along coasts, spatially ranging from microscopic scale (sediment grain size) all the way through the macroscopic scale (in the global scale, changes in sea level; e.g., Bird, 1985; Chen and Zong, 1998; Chen and Chen, 2002; Yang et al., 2005). For instance, waves are able to launch sediment along the coast by eroding the bottom sediment, transporting it with tidal currents and depositing it on an adjacent beach. Tidal cycles bring sand onto the beach and take it back into the surf zone (Bassoullet et al., 2000; Andersen et al., 2006), and rivers carry a large amount of sediment to the coast, thereby constructing deltas in the estuarine zones. Storms can cause severe erosion to coasts, taking away a great quantity of sediment and leaving thick overwash deposits in another location (Andersen et al., 2006). It is obvious that natural processes can influence the coast readily and repeatedly until some sort of equilibrium state is established.

Table 1. Assessment of coastal vulnerability around the Hainan Island

Objection	Factor	Index	Division standard	Risk classes
Coast vulnerability (*H*)	natural factors	coastal type	lagoon or sandy coast	–3
			muddy coast	–2
			sandy coast	–1
		sediment transport trend	offshore transport	–3
			onshore transport	–2
			alongshore transport	–1
		mean tidal range or significant wave height	significant wave height>2 m	–3
			significant wave height 0.5–2 m	–2
			significant wave height<0.5 m	–1
			mean tidal range>4 m	1
			mean tidal range 2–4 m	2
			mean tidal range<2 m	3
		mean SSC	offshore<0.05 kg/m^3	–3
			offshore 0.05–0.5 kg/m^3	–2
			offshore>0.5 kg/m^3	–1
			in a bay with estuary<0.05 kg/m^3	1
			in a bay with estuary 0.05–0.5 kg/m^3	2
			in a bay with estuary>0.5 kg/m^3	3
	human factors	urbanization level	>70%	3 or –3
			40%–70%	2 or –2
			<40%	1 or –1
		rank of sea area	first, 2nd class	3 or –3
			third, 4th class	2 or –2
			fifth, 6th class	1 or –1
	varied factors	erosion rate of coastline	high erosion>3 m/a	–3
			moderate erosion 2–3 m/a	–2
			low erosion 1–2 m/a	–1
		mean accretion rate of coastline	low accretion<1 m/a	1
			moderate accretion 1–5 m/a	2
			high accretion>5 m/a	3

Table 2. Coastline vulnerability assessment around the Hainan Island

Area	Influencing factor		Dynamic factor (*D*)	Vulnerability assessment (*H*)	Vulnerability assessment rank
	Natural	Human			
Haikou	–2.75	–2	–2	–2.25	moderate
Wenchang	–2.5	–1	–3	–2.17	moderate
Qionghai	–2.75	–1.5	–2	–2.08	moderate
Wanning	–2.25	–1	–1	–1.48	low
Lingshui	–2.0	–1	–1	–1.3	low
Sanya	–2.25/–2.75	–2	–1	–1.75/–1.92	moderate
Ledong	–2.0	–1	–1	–1.3	low
Dongfang	–2.25	–1	–1	–1.48	low
Changjiang	–2.5	–1.5	–2	–2	moderate
Danzhou	–1.75	–1	–1	–1.58	low
Lin'gao	–2.0	–1	–1	–1.33	low
Chengmai	–2.0	–1	–1	–1.33	low

Human activities, on the other hand, which include increasing coastal engineering and population growth, play an essential role in coastline change by the modifications the coastal environments and interferences of natural processes (Dai et al., 2013a). For example, dam construction on a river would result in a reduction of the sediment input into an estuary (Yang et al., 2005, 2011; Dai et al., 2010b, 2013a) and thereby lead to the coastal degradation. Therefore, influencing factors that affect on the erosion and accretion along coastlines are possible to couple with each other, eventually leading to a more complicated impact on the coasts.

As for the coast changes discovered in this study as described above, we suppose the SSC, sediment transport trends and sediment composition to be responsible for the generally stable state of coastlines in the nearshore zone of Sanya and Lin'gao as well as the accretion along the coastline of Beibu Gulf (Fig. 5): the coastlines near Sanya and Lin'gao are stable because of the relatively high SSC, onshore sediment transport (Fig. 4) trends and high sedimentation rate. The coastlines near the Beibu Gulf exhibit a heavy accretion as a consequence of the high values of

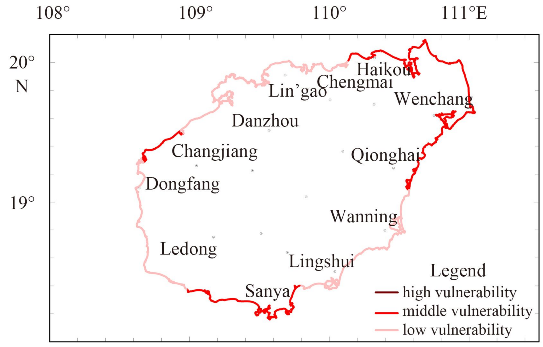

Fig. 6. Current beach vulnerability of the coast zone surrounding the Hainan Island.

both SSC and sedimentation rate (located in the shaded area of sediment transport center "I" in Fig. 4). This result corroborates the key role played by the presence of a sediment transport center in determining the coast change (accretion/erosion) within a given area.

5.2 *Vulnerability assessment*

It has been found in this study that the two major tourism cities—Haikou and Sanya—are threatened by an oddly moderate risk of coastal erosion, as weak or even no risk of erosion were expected based on the high SSC and stability of the nearby coastal zone (Figs 4 and 5). This moderate level of coastal vulnerability of Sanya are ascribed to (1) frequent hit of typhoons and storms along the southeast coast of Hainan Island, especially in the Sanya area, causing great damage to the local coastlines and constructions, (2) an enormous population that goes on increasing continuously with an increasing number of tourists to Sanya and (3) intense dynamics in the coast zone surrounding Sanya City.

Noticeably, the approach utilized in this study contributes to far more than a credible assessment of coastal vulnerability specifically in the Hainan Island alone as performed in this study. In a broader sense, it is applicable universally to the vulnerability assessment in other cases. As reported by numerous studies that coastline change, the erosion and recession of shoreline are caused by natural and human factors, leading to economic loss, in particular for cities with thriving tourism industries and well-known beaches (Bleta et al., 2009; Poulos and Chronis, 2001). It is imperative for local governments to grasp a good knowledge of the coastline vulnerability to erosion. Actually, in spite of a quantity of assessment methods that have been used to predict the extent of long-term coastal erosion and accretion, e.g., CVI, CSoVi (a social vulnerability index) and DIVA (Dynamic Interactive Vulnerability Assessment; Abuodha and Woodroffe, 2007), none of them has been turned out entirely satisfactory for (1) the complication involved in the practical operations as most of these approaches are created on the basis of the Bruun Rule, (2) difficulties of the quantification of the socio-economic variables included in many of the approaches as well as the resultant errors of the assessment and (3) non-universal adaptability to other vulnerability assessments. Being derived from a simple equation on account of both natural and human factors as elaborated above, the methodology of vulnerability assessment proposed in this study provides as a valuable tool for the government departments responsible for the coast management in both Hainan Island, and other coastal zones in the world (with some adjustments depending on the local conditions if needed). That is, it serves as a simple yet effective method with a universal adaptability to realize an efficient assessment of coastal vulnerability

Plenty of further work is still required in order to mitigate coastline vulnerability to the best in the future, including (1) to constrain the annual frequency, timing and magnitude of major storms and (2) to quantify the impact of each individual influencing factor on the coastal changes.

6 Conclusions

In this study, we analyzed coastline change utilizing charts from different years, and assessed the vulnerability of the coast surrounding the Hainan Island based upon human activity (primarily the level of urbanization) and natural processes (seabed sediment transport and SSC). It turned out that the four major cities of the study area, i.e, Haikou, Wenchang, Sanya and Changjiang, have a coastline that is overall stable, but they also have a moderate coastal vulnerability at the same time owing to human activities. This result indicated that human activities play such an important role in coastal vulnerability that should never be neglected in such assessment, in particular for areas with large populations like the Hainan Island. Further, this integrated assessment methodology serves as an effective tool with a universal adaptability to derive a better understanding of coastline change and vulnerability for governments and coastal management departments all over the globe.

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