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Characteristics of Spatial and Temporal Evolution of Sandy Coastline in Shuidong Bay based on Remote Sensing Images

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Abstract: In this study, 77 periods of Landsat TM/OLI remote sensing image data of Shuidong Bay from 1987 to 2021 were used to extract the sandy shoreline of Shuidong Bay. A visual interpretation method was employed to analyze the sandy shoreline of this beach over the past 30 years. This involved examining the shoreline erosion or siltation, the linear or non-linear process of the beach, and the main patterns of beach evolution. A spatio-temporal evolution characterization study was conducted. The results demonstrated that: (1) The shoreline change of Shuidong Bay in the past 30 years is mainly stable (49.3%), with erosion or siltation occurring primarily in the middle and east side of the beach. The maximum siltation rate was 2.65 m/a, while the maximum erosion rate was -2.50 m/a. (2) There are three main evolutionary trends in Shuidong Bay. The evolution of Shuidong Bay can be divided into three main categories: linear, non-linear, and non-linear with a linear component. The linear process is primarily observed on the west side of the beach, while the non-linear process is concentrated on the south side. On the east side of the beach, the non-linear process is the dominant force shaping the shoreline. The linear process accounts for 61.2% of the total area. The first mode spatial coefficients of Suidong Bay are highly similar to the graphs of the LRR values, which further verify the main spatial pattern of the shoreline of Suidong Bay. This pattern can be described as a temporal reversal of the trend of siltation along the shoreline before 2003, followed by erosion along the shoreline after 2003. This paper presents an analysis of the evolution of the sandy coastline in Shuidong Bay. The results provide a valuable foundation for the development, utilization, management, and protection of coastal zone resources in Shuidong Bay.

Keywords: Sandy Coast; Spatial and Temporal Evolution Characteristics; Nonlinear Process; DSAS; Landsat Image.

1. Introduction

Sandy coasts, as an important part of the coastal zone, have great tourism value and are gradually becoming one of the most anthropologically active coastal types among all coasts [1]. Globally, 70% of sandy beaches are subject to erosion, and almost all open muddy shores and about 70% of sandy shores in China are subject to erosion [2, 3, 4]. The negative impacts of sea-level rise and human activities are continuously exacerbating the erosion of sandy shores. Pollution and ecosystem degradation have also had many impacts on sandy shores [5-7]. In particular, the retreat of sandy coasts due to extreme events such as storm surges poses a major threat to the safety of human life and property, such as typhoon events causing extensive damage on islands [8]; and the erosion of the 254 km of sandy coastline in the Netherlands due to insufficient supply of nearshore sediment as a result of anthropogenic sand mining [9]. Whether from the point of view of geoscientific research, healthy economic growth, or sustainable development of human society, research on the evolution process and driving mechanism of sandy shorelines can effectively provide services to human activities [10, 11].

In China, the national standard "Oceanographic Terminology Marine Geology" (GB/T 18190-2000) stipulates that the line where the mean high tide level intersects the coastline is the spatial location of the coastline, i.e., the mean high tide line [12]. In the 1830s, a variety of aerial photogrammetric images became an important source of information acquisition on the coastline [13]. Since the 1970s, with the launch of Landsat, remote sensing images have gradually become a hotspot for researchers due to the advantages of wide coverage, short cycles, high resolution, and so on. Among them, the Landsat series of remote sensing image data are the most widely used [14], and IKONOS, WorldView, SPOT, etc. have also been widely used [15-17]. At present, there are two main shoreline extraction methods commonly used at home and abroad, and the first one is computer-based automatic water margin extraction with tide level correction [18]. McFeetes, Xu Hanqiu, Li Ming, and Zheng Xiaoshen applied to the automatic extraction of water margins through the continuous improvement of the water body index method and combined with the threshold segmentation method [19-21]; Liu Xiaoli et al. and Bing Liu et al. used the edge detection method, Liu et al. and Bing Liu et al. respectively. used the edge detection method to extract the water edge of sandy shoreline and Yangtze River, respectively, and evaluated and analyzed the results [22, 23]; Cui Dandan et al. Proposed the tidal zonal correction method, which is based on the analysis of the tidal adjustment at the control point, and used the tidal linear zonal interpolation correction process to assign the actual tidal level to the discrete points of the water's edge, and then deduced the location of the mean slope and the high tide of the mean high tide [24]. The second is to extract the high tide shoreline by visual interpretation based on existing shoreline interpretation standards and experience [25].

With the development of RS and GIS technologies, domestic researchers have carried out the analysis of coastline evolution based on various types of remote sensing images in terms of coastline length, intensity of change, fractal dimension, regional land area, and rate of change. Foreign researchers, on the other hand, preferred to use the rate of change to measure the spatial trend of the coastline, among which the endpoint rate method [26], the average rate method [27], and the linear regression rate method [28] have been widely used in recent years. Thieler et al. provided a detailed description of the use of DSAS for coastline analysis [29]; Mahapatra et al. used the DSAS LRR method in DSAS to analyze the data along the coastline of South Gujarat, India, extracted from 4-period remotely sensed imagery from 1972-2011 [30]. However, the rate of change calculation method essentially assumes that the change in the coastline is uniform per unit of time, whereas it has been shown that the coastline tends to exhibit nonlinear change when affected by various natural or anthropogenic factors. Fenster et al. To understand the nonlinear process of shoreline evolution, the Minimum Description Length (MDL) criterion was used to discriminate whether the rate of change of the historical shoreline has undergone significant changes in the rate of change and when they occurred [31]; Zhu Luoyun et al. further introduced the M-K trend test to try to reveal the time nodes of erosion or siltation trend shifts in 17 sandy beaches in eastern Guangdong in the past 30 years [32]. Thus, the analysis of coastal evolution with non-linear changes and "correlation" as the problem orientation may become a hot spot for domestic and international research in the future.

Based on this, this paper takes Shuidong Bay as the research object and conducts research on the evolution characteristics of the sandy shoreline in Shuidong Bay over the past 30 years by extracting the sandy shoreline from 77 periods of Landsat remote sensing images from 1987 to 2021. The main objectives of this paper include (1) to analyze the rate change characteristics (erosion or siltation or stability) of the sandy shoreline in Shuidong Bay and to evaluate the linear or nonlinear evolutionary processes of the shoreline; (2) to grasp the spatial distribution of the linear or nonlinear processes of the sandy shoreline in Shuidong Bay and to reveal the main evolutionary patterns of the sandy shoreline in Shuidong Bay. The results of the study will provide scientific decisions for the protection and sustainable use of the sandy coastline of Shuidong Bay.

2. Study Area Overview and Data Sources

2.1. Study Area

Shuidong Bay is located in Dianbai District, Maoming City, Guangdong Province, and is known as the 'Beidaihe of the South', as shown in Figure 1. As the main area of coastal development and construction in Maoming, the Shuidong Bay area has the important task of developing Maoming's new urbanization and is expected to become a "new urbanization pioneer and experimental area of the east and west wings of Guangdong". This area has a pleasant climate and is located in the northern tropical and southern subtropical transition zone, the geographical environment is unique, depending on the mountains and the sea, complex and diverse geomorphology, belonging to the tropical and subtropical monsoon climate zone. Compared to Ao Nai Wan, Boga Bay, and other different, Shuidong Bay exists mainly in the tourism value, and tourism-oriented beaches, it is very likely that there are artificial sand filling and replenishment and other processes to change the original power mechanism of the beach localization.

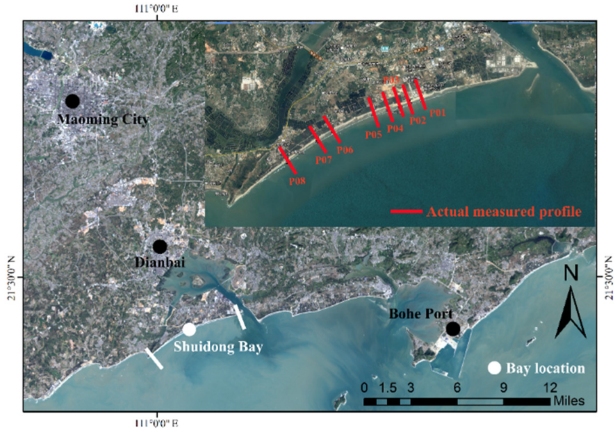

Fig 1. Geographic location of the study area and distribution of measured profiles

2.2. Data Sources

In this paper, the 1987-2021 Landsat TM/OLI image data from Geospatial Data Cloud (http://www.gscloud.cn), which can completely cover the sandy coastline of Shuidong Bay, with image row and column number 123/45, and the spatial resolution of the image is 30m, and a total of 77 views of the image were selected. To verify the accuracy of the sandy coastline extraction, this paper also uses the mean high tide line position data of eight profiles in Shuidong Bay collected by three field operations in summer 2016, summer 2017, and autumn 2019, which were field measured by Hopscotch RTK-GPS (CGCS2000 coordinate system) (Fig. 1).

3. Methods

3.1. Shoreline Extraction and Accuracy Assessment

Due to the uneven slope of the tidal beach and its dynamic height change, the computer-based tide level correction model may not be applicable to the actual situation of the beach, so this paper adopts the visual interpretation method to deal with the sandy shoreline of Shuidong Bay. Before extracting the shoreline, the remote sensing images used should be pre-processed, and the Landsat images are pre-processed by image cropping, radiometric calibration, and atmospheric correction using ENVI 5.3, and then the red, green, and blue are defined by the 5th, 4th, and 3rd bands in ArcGIS 10.8 for TM and ETM+ images, and the combination of the 4th, 5th, and 6th bands is applied to the images of OLI. The high tide shoreline of Shuidong Bay was extracted by using the boundary line between bright white and dark grey areas as the decoding marker [33,34]. To verify the extraction accuracy of the interpreted shoreline, this paper calculates the vertical distance from the measured point to the interpreted shoreline based on the point data of the measured high-tide shoreline and the nearest interpreted shoreline at the corresponding time in ArcGIS 10.8, which is used as the shoreline extraction error, and adopts the root mean square error to evaluate the accuracy of the shoreline extraction. The calculation principle is as follows:

$$RMSE = \sqrt{\frac{D_1^2+D_2^2+\cdots+D_n^2}{n}} \tag{1}$$

where RMSE is the root mean square error, D is the vertical distance from the measured climax shoreline point to the interpreted shoreline, and n is the number of measured validation points (n=3 in this paper).

3.2. Section-based Linear Regression Rate of Change

The Digital Shoreline Analysis System (DSAS) is a tool for the quantitative study of shoreline change based on the ArcGIS platform [29]. In this paper, the linear regression rate (LRR) method in DSAS is used to calculate the shoreline change rate over the past 30 years, which is the average rate of shoreline change obtained by using the least squares method to fit the location point where the cross section intersects the shoreline at all times, and the calculation principle is as follows:

$$y = Ax + B \tag{2}$$

$$A = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{3}$$

$$B = \bar{y} - A\bar{x} \tag{4}$$

where y is the distance of the shoreline from the baseline in the section, x is the numerical time of the corresponding image of the shoreline, and A is the LRR.

3.3. Linear or Non-linear Evaluation of Shoreline Evolution Processes

Shoreline evolution is often approximated as a linear process. For example, the endpoint rate (EPR) method, linear regression rate (LRR) method, weighted linear regression rate (WLRR) method, and other shoreline rate calculation methods recommended in DSAS are essentially linear evaluations of shoreline evolution. Commonly used non-linear evaluation methods include second-order polynomial models, high-order polynomial models, exponential models, logarithmic models, and so on. Among them, polynomial models have been more widely used in recent years because of their clear physical meaning. For example, the second-order polynomial model indicates a significant change in the long-term shoreline trend [35], while the third-order polynomial model indicates two significant changes in the shoreline trend [36]. In order to reveal more deeply the process and characteristics of shoreline evolution in the direction of the vertical shoreline, and to be able to better correlate with the driving factors, this study proposes to use the first-order polynomial model (y=Ax+B) and the second-order polynomial model ($y=Ax^2+Bx+C$) to comparatively evaluate whether the shoreline evolution of the study area in the last three decades is dominated by a linear or non-linear process, and accordingly correlate it with the driving factors of shoreline evolution.

3.4. Empirical Decomposition of Orthogonal Functions

Empirical Orthogonal Function Decomposition (EOF), also known as Principal Component Analysis, is a statistical method for downscaling data to analyze the structural characteristics and extract the main eigenvectors. EOF was first applied in the field of atmospheric sciences, and the principle of EOF is to decompose a two-dimensional numerical matrix into a series of spatial and temporal eigenvectors that are orthogonal to each other and can express the main characteristics of the data in both spatial and temporal dimensions [37,38]. These eigenvectors are orthogonal to each other and can effectively express the main characteristics of the data in both spatial and temporal dimensions [37,38], which can be used in the beach evolution analysis to reveal the main evolution patterns of the beach in both space and time to a certain extent. The computational principle and process of EOF are as follows:

(1) Construct the original value matrix Bm×n, with the section serial number as the row m, the beach extraction time as the column n, and the distance of the beach from the baseline on the section as the value;

(2) Standardise and distance level the original value matrix to obtain the standardized distance level matrix Cm×n;

(3) Calculating the correlation coefficient covariance matrix Dm×m of the standardized distance level matrix;

$$D_{m\times m} = CC^T \tag{5}$$

C^T is the transpose $of\ C$;

(4) Calculate the eigenvalues (λ_1, λ_2...λ_m) and eigenvectors $V_{m\times m}$of $D_{m\times m}$, arrange the eigenvalues λ_k (k=1,2...m) and the corresponding eigenvectors V in the order of the eigenvalues in ascending order of the eigenvalues V. The eigenvectors V corresponding to the eigenvalues λ_k are the spatial coefficients of the EOF decomposition;

(5) calculating the corresponding time coefficient of the spatial coefficient $PC_{m\times n}$,

$$PC_{m\times n} = V_{m\times m}^T C_{m\times n} \tag{6}$$

(6) Calculate the variance contribution c_k for the kth mode corresponding to the kth eigenvalue λ_k,

$$c_k = \frac{\lambda_k}{\sum_{k=1}^{m}\lambda_k} \times 100\% \tag{7}$$

4. Results of the Study

4.1. Erosion or Siltation of the Shoreline

In this paper, based on the set section, the LRR of Shuidong Bay in different sections in the past 30 years was calculated by DSAS in ArcGIS and used as the rate of shoreline change, based on the criterion that the rate of shoreline change of the stable shoreline was classified as <0.5m/a by Esteves and Finkl and Luijendijk et al. [2], it can be assumed that: if the rate of change is greater than 0.5m/a, the shoreline is classified as a siltation shoreline; if the rate of change is in the range of -0.5 to 0.5m/a, the shoreline is classified as a stable shoreline; if the rate of change is less than -0.5m/a, the shoreline is classified as an erosion shoreline. As shown in Fig. 2, a total of 77 Landsat imagery data were used in Shuidong Bay, and 201 effective sections were set from the west side to the east side of the beach at a distance of 50 m. The results show that the sandy shoreline of Shuidong Bay remains stable in sections T1-T80, siltation occurs in sections T81-T152 (except for T93-T94), stability is maintained in sections T153-T166, erosion occurs in sections T167-T201, and erosion occurs in sections T167-T201. The maximum siltation rate is at T140 (2.65 m/a), the maximum erosion rate is at T191 (-2.50 m/a), and the average rate of change of the whole shoreline is 0.31 m/a. Further statistics show that in the past 30 years, a total of 32 sections in Shuidong Bay have eroded (15.9%), and 99 sections have been in the past 30 years, a total of 32 sections have eroded (15.9%), 99 sections have been stable (49.3%), 70 sections have been silted (34. 8%), and the spatial distribution of 'stability-silting-stability-erosion' occurred along the shoreline from west to east, with stability dominating the west side of the shoreline, siltation dominating the central part of the shoreline, and erosion dominating the east side of the shoreline.

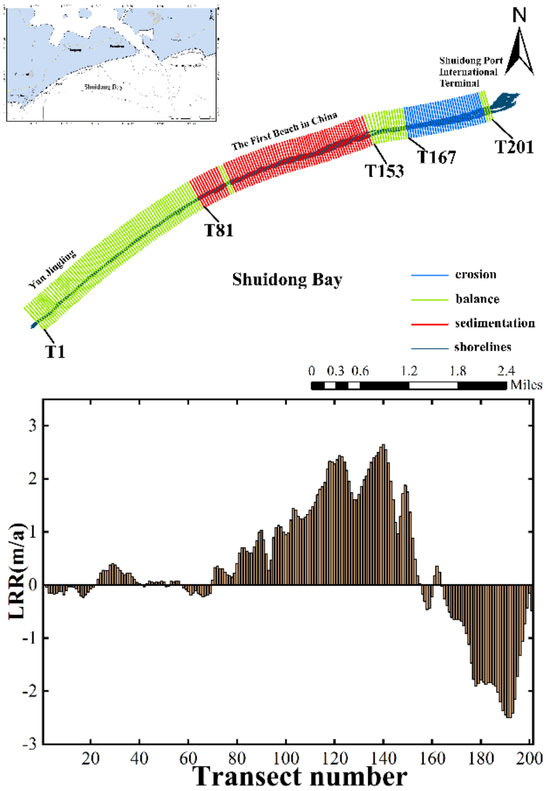

Fig 2. Erosion or siltation in Shuidong Bay (left) and LRR on each section (right)

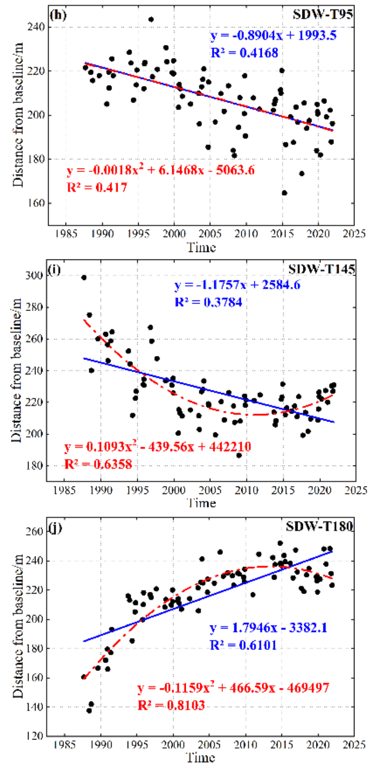

Fig 3. Main evolutionary trends and linear/non-linear processes of the sandy shoreline of Shuidong Bay in cross-section

4.2. Linear or Non-linear Processes and Spatial Distribution of Beach Evolution

In order to further reveal the more detailed evolution process of the sandy shoreline in the section and the main linear or non-linear change trends of the beach in the section, this paper calculates the distance from the shoreline along the direction of the section to the baseline as the positional data of the sandy shoreline in each period, based on the section laid in Shuidong Bay and the baseline laid on the seaward side of the shoreline (asymptotically larger distance from the baseline, shoreline erosion occurs, and vice versa siltation occurs). Linear and quadratic polynomial models were used, based on the R2 value of the model fitting results; when the R2 value of the quadratic polynomial model was significantly greater than that of the linear model, the process of shoreline change was more likely to be a non-linear process, whereas when the R2 value of the linear model was similar to that of the quadratic polynomial model, or when both models were not good (R2value was very small), the shoreline was considered to be influenced by the extraction error of the 30m remotely sensed image, the shoreline change processes within the acceptable error range are all considered to be linear processes. The results in Figure 3 show that there are three main evolutionary trends of the sandy shoreline in Shuidong Bay, as shown in Figure 3(h), Figure 3(i), and Figure 3(j). Figure 3(h) shows that the shoreline in the section generally occurs with time the gradual siltation of the shoreline linear process; Figure 3(i) shows that the shoreline in the section is siltation of the shoreline before 2010, the gradual erosion of the shoreline after 2010 reversal of trend, the overall occurs with time the shoreline siltation followed by erosion of the non-linear process; Figure 3(j) shows that the shoreline in the section there is siltation of the shoreline before 2010, the erosion of the shoreline in 2010, the erosion of the shoreline in 2010, the erosion of the shoreline in 2010.

In order to further reveal the spatial distribution of linear or non-linear processes at beach locations in Shuidong Bay, this paper is based on the sections set in Shuidong Bay, and the linear or non-linear processes at different sections are taken to be binarised. The results of Shuidong Bay in Fig. 4 show that in the past 30 years, the sandy shoreline of Shuidong Bay occurs linear processes on sections T1-T80, T91-T120, T128-T132, T150-T157, and non-linear processes on sections T81-T90, T121-T127, T133-T149, T158-T201, and further statistics, Shuidong Bay sets a total of 201 effective sections, of which 123 sections occurred linear processes (61. 2%) and 78 sections occurred non-linear processes (38.8%), linear processes occurred mainly on the west side of the beach, non-linear processes occurred mainly on the east side of the beach, and the shoreline was dominated by linear processes.

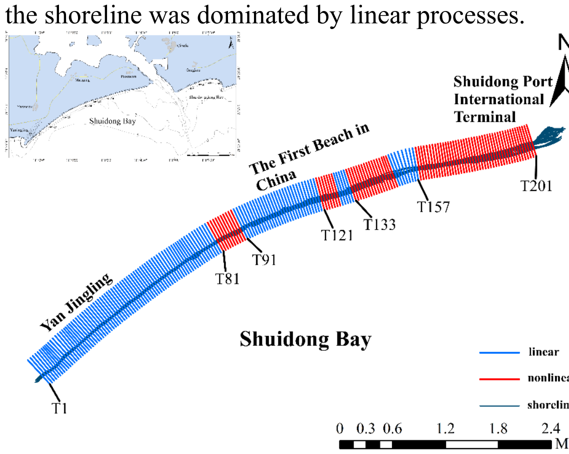

Fig 4. Spatial distribution of linear/nonlinear processes along the sandy shoreline of Shuidong Bay

4.3. Main Patterns of Beach Evolution

In order to further reveal the main evolution patterns of Shuidong Bay in the spatial and temporal dimensions over the past 30 years, this paper takes the distance from the baseline along different sections of each interpreted shoreline as the basic data and constructs the original numerical matrices with time and space as the row and column numbers. The 0.5-year equally spaced linear interpolation, normalization, and distance leveling are applied to the original matrix to obtain the target matrix, which is then subjected to EOF decomposition, and the variance contribution ratio and cumulative variance contribution ratio of the first four modes in Shuidong Bay (Table 1), and the spatial coefficients and temporal coefficients corresponding to the first mode (Fig. 5) are finally obtained. Related studies have shown that when the natural orthogonal function decomposition contains more than 7 factors (all factors in the objective matrix of this paper are more than 7), the proportion of the variance contribution rate of the first mode is about 30% [39]. The results of Shuidong Bay show that the 1st mode variance contribution rate of Shuidong Bay is 38.5% (Table 1), as shown in Fig. 5 (SDW(a)), the spatial coefficients of the shoreline are mainly positive in sections T1-T7, T16-T19, T57-T69, and T165-T201, and mainly negative in sections T8-T15, T20-T56 and T70-T164, which indicates that Shuidong Bay has the same change pattern in sections T1-T7, T16-T19, T57-T69, and T165-T201, while the changing pattern in sections T8-T15, T20-T56, and T70-T164 is the opposite; Figure 5 (SDW(b)) shows that the time coefficients of the pre-2003 shoreline are mostly negative, and the time coefficients of the post-2003 shoreline are all positive values, indicating that the shoreline has undergone 1 reversal of the changing trend around 2003. From the LRR of the sandy shoreline of Shuidong Bay in different sections and the main development trend of the shoreline in sections over time in the past 30 years, it can be seen that there is erosion in Shuidong Bay in sections T1-T7, T16-T19, T57-T69, T165-T201 in space, siltation in sections T8-T15, T20-T56, T70-T164 and siltation in section T8-T15, T20-T56, T70-T164 in time, and shoreline siltation in Shuidong Bay before 2003 and shoreline siltation before 2003 and shoreline siltation after 2003. The main development pattern of shoreline siltation and shoreline erosion after 2003.

Table 1. Variance contribution and cumulative variance contribution of the first four modes in Shuidong Bay

Beach Name	Modal	Variance contribution (%)	Cumulative contribution (%)
Shuidong Bay	1	38.5	38.5
	2	20.3	58.8
	3	11.0	69.8
	4	5.8	75.6

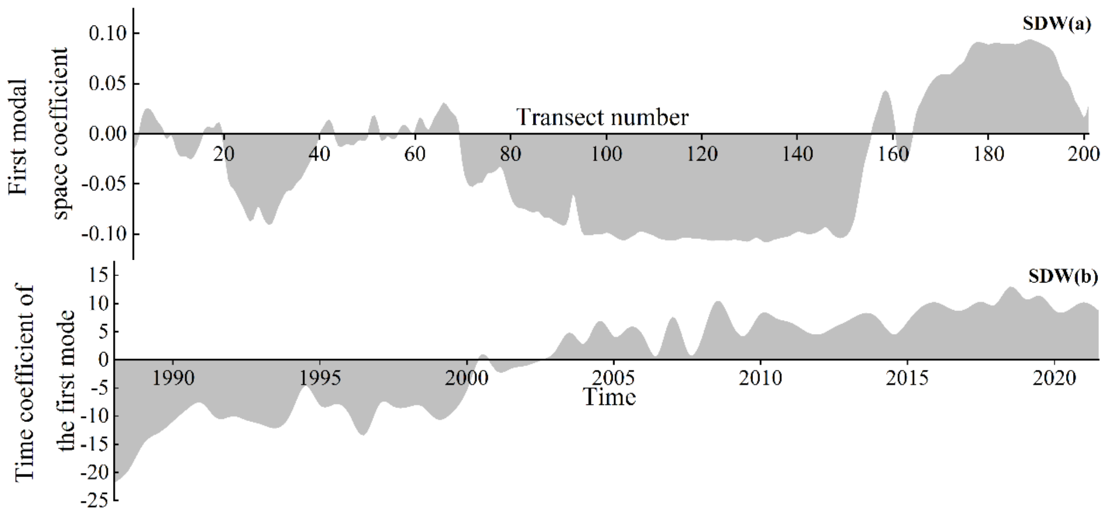

Fig 5. Distribution of spatial and temporal coefficients for mode 1 in Shuidong Bay

5. Discussion

5.1. Shoreline Extraction Accuracy

Remotely sensed image-deciphered coastline data are the basis for the subsequent analysis of the long-term spatial and temporal evolution of coastline features, and due to the influence of instrumentation, environment, and human factors, the process and results of coastline deciphering are always accompanied by the generation of errors. In this paper, based on the average high tide line position data of eight profiles collected in three field operations in summer 2016, summer 2017, and autumn 2019, the RMSE of the imaged coastline at the profile corresponding to the measurement time was calculated in ArcGIS using the method of making the difference of the distance of the point line along the profile (Table 2). Hou Xiyong et al. proposed that the "theoretical maximum permissible error" of coastline extraction from 30m resolution remote sensing imagery is 28.28m [40]. According to this paper, it can be concluded that among the eight profiles measured in Shuidong Bay, the RMSE of the interpreted coastline at P04 is the smallest at 7.87m, and the RMSE of the interpreted coastline at P05 is the largest at 14.64m, and the average RMSE of Shuidong Bay is 12.22m, and the actual error of beach shoreline interpretation at the profiles is less than the "theoretical maximum permissible error". The actual errors of shoreline interpretation at the profiles are all less than the 'theoretical maximum allowable error'. Therefore, the sample data calculated in this paper are all measured in the field, so the extraction results of sandy coastline remote sensing interpretation in Shuidong Bay in this paper meet the requirements of error accuracy. Zhu Luoyun in the extraction of the coastline of 17 Cape Bay beaches in east Guangdong there are 12 bays in the extraction error within 1 image (30m), while the other 5 bays have a certain deviation, which is analyzed as a result of the lack of synchronous observation, that is, the time gap between the field observation time and the corresponding image time is large, and in the middle of the time, it may be subject to the impact of the typhoon event, etc., caused by the climax of the coastline. Caused by the climax of the coastline changes [33], this paper on the ShuiDongBay In this paper, the sandy coastline of Shuidong Bay is treated with a smaller gap between the observation time and the corresponding image time, and the influence of typhoon events has a certain stage, so the extraction results in this paper will be more reliable.

Table 2. Evaluation results of sandy shoreline extraction accuracy in Shuidong Bay

Beach Name	Real section	Actual measurement time	Image time	RMSE (m)	Average RMSE (m)
Shuidong Bay	P01	2016/07/26 2017/07/23 2019/10/28	2016/07/23 2017/09/12 2019/11/05	12.76	12.22
	P02			12.24	
	P03			10.29	
	P04			7.87	
	P05			14.64	
	P06			14.53	
	P07			14.06	
	P08			11.36	

5.2. Spatial and Temporal Evolution of the Coastline

To evaluate the total erosion or siltation in Shuidong Bay over the past 30 years, this paper used the linear regression rate (LRR) method and classified the evolution of the sandy shoreline in Shuidong Bay in terms of change (erosion, siltation, and stabilization) on a cross-section based on the criteria given by Esteves and Finkl and Luijendijk et al [2]. Researchers often use several methods simultaneously to calculate the rate of shoreline change, such as Zhu Luoyun et al. and Zhang Xiang et al. who mainly used the EPR and LRR methods to calculate the rate of shoreline change [32,41], and Bu Ting and Hou Xiyong who mainly used the EPR, WLRR and AOR methods to calculate the rate of shoreline change in Jiaozhou Bay from 1944 to 2012 [42]. In this paper, only the LRR method is used to calculate the rate of change of the shoreline because the LRR method is based on the principle of least squares and is mainly used for qualitative judgment and quantitative calculations, and compared with the EPR method, the LRR method is more reliable due to the use of more data samples.

In this paper, linear and quadratic polynomial models were mainly used to analyze the linear or nonlinear processes in the long-term evolution of Shuidong Bay. From the results of the linear or non-linear analysis of the beach evolution, it can be seen that there are three main evolutionary trends in Shuidong Bay, two of which are non-linear processes and one of which is a linear process. The main evolutionary trends reflect the change of the shoreline on the section, which usually can be observed through the fitting results of the shoreline on the section roughly when there is a change of trend shift, for this paper, this paper will not be further explored in the section of the shoreline change exists a few times of trend shift. Further research has shown that the linear regression rate (LRR) method is based on a linear fit to the rate of shoreline change, which is sufficient to show that for beaches such as Shuidong Bay, which are dominated by linear processes, the LRR can be considered as the basis for the rate of change of sandy shoreline in Shuidong Bay.

For profiles dominated by nonlinear processes, the results calculated by the least-squares method of shoreline change rate are theoretically unreliable, and the shoreline change rate indicates that the shoreline has a uniform change per unit of time, which is non-uniform [34]. The results of the linear and nonlinear evaluations in this paper also indicate that the sandy shoreline at a certain point in time has a shift in the trend of change or even a reversal. To better reveal the spatial and temporal evolution characteristics of the sandy shoreline in Shuidong Bay, the results of the empirical orthogonal function decomposition in this paper illustrate the main evolution modes of the sandy shoreline in Shuidong Bay in the temporal and spatial dimensions. Since the variance contribution of the first mode of Shuidong Bay is the largest and more than 30%, this paper focuses on the spatial and temporal functions of the first mode of Shuidong Bay. Based on the positive and negative spatial functions to judge the main erosion or siltation conditions of Shuidong Bay in different sections, and comparing the calculation results of the LRR of Shuidong Bay in the erosion or siltation conditions of the shoreline, it is found that the spatial coefficients of the 1st mode of Shuidong Bay are very similar to the graphs of the LRR values, which further validates the main spatial development pattern of the shoreline in Shuidong Bay. Based on the positive and negative time functions to determine the turning points of the shoreline change trends in Shuidong Bay, and comparing the main change trends of the long-term evolution of Shuidong Bay in the linear or nonlinear analysis of beach evolution, it is found that the time coefficient of the 1st mode of Shuidong Bay has only one significant turning point, which indicates that the evolutionary pattern of Shuidong Bay has undergone a significant change in the temporal dimension over the past 30 years. This explains the relevance of the EOF results for Shuidong Bay.

6. Conclusion

The full paper takes Shuidong Bay as the research object, establishes the sandy coastline dataset of Shuidong Bay by visual interpretation based on the 77-scene Landsat remote sensing images from 1987 to 2021, and evaluates the accuracy of the sandy coastline extraction of Shuidong Bay based on the information of three field surveys from 2016 to 2019 using the root mean square error method. The spatial and temporal evolution characteristics of the sandy coastline of Shuidong Bay were investigated by using the linear regression rate method, linear or nonlinear evaluation, and empirical orthogonal function decomposition, and the following conclusions were drawn:

1. The sandy coastline of Shuidong Bay has mainly remained stable over the past 30 years, with the changes in coastline siltation mainly occurring in the middle of the beach and the changes in erosion mainly occurring on the eastern side of the beach.

2. Over the past 30 years, both linear and non-linear processes have occurred in Shuidong Bay. The linear process is mainly manifested in the erosion or siltation of the shoreline over time, and the non-linear process is mainly manifested in the shoreline in the cross section from a certain moment, and the change of trend has been transformed or reversed. Shuidong Bay is dominated by linear processes.

3. The empirical orthogonal function decomposition makes up for the shortcomings of the linear regression rate method for non-linear processes and better reveals the main development patterns of Shuidong Bay in time and space dimensions.

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