Analyzing the Topographical Evolution Characteristics of a Bay over the Last 50 Years

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Abstract

Based on coastline, water depth, and remote sensing image data of Sanmen Bay over the past 50 years, this research analyzed quantitatively coastline temporal-spatial evolution characteristics and underwater topography evolution characteristics. The results showed that the total coastline length of Sanmen Bay first decreased and then increased during the last 50 years. The most obvious change of total coastline length occurred from the 1960s to the 1990s. However, in this period, the natural coastline had a higher percentage and a slower change rate. After the 1990s, with artificial interference gradually increasing, the coastline experienced a change process of the curving coastline becoming a straight coastline and moving outward continually. Although the length variation is small, the spatial form of the bay has changed significantly. After 2007 the artificial coastline accounted for more than 70%. From the 1960s to 2015, coastline and 0 meter isobath showed the trend of moving outward. The bay area decreased and most channels deposited. In general, the underwater topography in 2015 was more complex than that in the 1960s. Human activity had a critical role of affecting branch development in the Sanmen Bay area.

Keywords: coastline, Sanmen Bay, evolution characteristics, erosion and deposition, underwater topography

Introduction

A bay area is a border region of land and sea. As one of the most frequent material and energy exchange areas, bays are easily affected by eustasy, diastrophism, and changes in land-sea distribution [1-3]. Coastal zones located in the concentration areas of population and economic activities have fragile geological and ecological environment, and increasing contradictions of resources and environment problems [4-7]. As development and utilization continue, human activities such as land reclamation, coastal engineering construction, and aquaculture make great contributions to gulf economic development, while at the same time bringing many negative effects [8-9]. Reclaiming the land from the sea causes a decrease in bay area and the tidal prism, and reduces tidal current velocity, which leads to gulf siltation and affects water exchange [10-13].
Sanmen Bay is a typical semi-closed strong tide bay with multiple channels and has a certain representativeness in coastal bays of Zhejiang Province [14-16]. There are multiple islands in the bay and long coastline twists and turns. A multistage branching stream embedded inland and alternated arrangement with a large lingulate tidal flat constitute a unique landscape of the Zhejiang-Fujian coast. This area holds significant economic status in Zhejiang, which has been driving a continuous reclamation project for a long time [17-19]. Under the marine resources development boom, the influence of human activities on Sanmen bay has far more than the role of natural influence. In the face of great environmental pressure, human concerns began to pay more attention to ecological and environmental benefits instead of only the pursuit of economic interests [20-24].

This research aimed to disclose landform evolution characteristics in Sanmen Bay within the last 50 years. First we analyzed quantitatively the coastline temporal-spatial evolution process from the 1960s to 2015, and calculated the changing rate of coastline length in different periods. Secondly, in order to explore underwater topography evolution characteristics we analyzed isobath distribution from the 1960s to 2015, calculated volume and area of subwater topography erosion and deposition, and researched erosion and deposition distribution characteristics of the main branching streams.

Material and Methods

Study Area

Sanmen Bay is located in the central coastline of Zhejiang Province across Ninghai, Xiangshan, and Sanmen counties. It is NW-SE oriented, with the northern neighbor being Xiangshan Harbor and the southern one Taizhou Bay. Its latitude and longitude range from 28°57′N to 29°22′N, and from 121°25′E to 121°58′E, respectively.

The study area has a subtropical monsoon climate with four distinct seasons, moderate weather, and abundant rainfall. The annual average precipitation is 1375.3 mm, with more than 80% falling in the period from March to September. The annual average wind speed ranges from 1.9 to 5.6 m/s, and the annual average number of fog days ranges from 13 to 54.6.

Sanmen Bay has bedrock coast and muddy coast, as well as artificial coastline. Numerous islands in the bay weaken the dynamic effect, along with a certain fine particulate matter source, and the muddy coast is so well developed. This bay has abundant tideland resources, with branching streams embedded in lingulate tidal flat. Tidal prism is considerable, with a mean tidal range of 4 m. Tidal range increases gradually from the bay mouth to the northwest inside the bay. The tidal current is of an irregular semi-diurnal one. The flood tidal duration is larger than the ebb tide, while the flood current velocity is slower than the ebb current in the whole tidal process. And the seasonal variation is not obvious. The maximum flood is 155 cm/s, ebb is 179 cm/s.

Data Source

For researching landform evolution characteristics of Sanmen Bay with a longtime scale, this study involved different plotting scales and data sources, including mainly coastline, water depth, remote sensing image, and auxiliary data.

Coastline Extraction

First, coordinate systems of five phases of coastline data must be unified because of different coordinate reference systems and the projection mode of the spatial data from different sources [25-27]. The coastline data adopted CGCS2000 coordinate systems and Gauss-Kruger projection of central longitude 120 degrees.

Coastline in the 1960s was extracted from a Landsat TM remote sensing image map of 1964. First, the remote sensing image was enhanced to improve contrast. In the meantime, the coastline was modified with reference to the sea and aviation maps. The coastline was classified into two types: artificial and natural coastlines. Artificial structures were mainly constructed by cement and stone, and had relatively high spectral reflectance. External edges of the dyke were taken as artificial coastline. The natural coastline was the line of water and land boundary [28-30].

Coastline in 1990s was extracted from the sea map of Sanmen Bay, which was measured in 1998. The coastline was also classified into artificial
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Coastline Variation Rate Calculation

Based on multiple periods of historical coastline data, coastline variation rate was calculated by adopting the endpoint rate method to analyze coastline change characteristics [31-32]. This method divides the moving distance between two positions by time lag, and the formula is as follows:

\[ \text{EPR} = \frac{D_2 - D_1}{T_2 - T_1} \]  

...where \( D_1 \) and \( D_2 \) are the position data of time \( T_1 \) and \( T_2 \), respectively.

Water Depth Data Processing

Change of erosion and deposition was affected by various factors such as water and sediment transport, suspended load, and bed load movement [33-38]. A large volume of sediment deposition will lead to a barred dam, which is disadvantageous to water exchange [39-41]. It is important in its actual significance and practical application value to research underwater topography evolution characteristics [42-44]. Water depth data contained two periods of data: in the 1960s and 2015. The data of the 1960s, collected from a sea map of Sanmen Bay, was first vectorized and its coordinate system unified to CGCS2000. The data was analyzed by ARCGIS 10.3.

(1) Create TIN: Creating a TIN model by first using the 3D Analyst extended module. After model generation we can add, remove, or modify the TIN node and intersecting line directly to make the model more reasonable with real-time feedback of the model surface.

(2) TIN to Raster: After all the TIN models generation, converting TIN to Raster files for calculating volume and area of erosion and deposition.

(3) Erosion and deposition variation: Digital erosion and deposition variation maps could be obtained by making overlay analysis of two periods of raster files with “Minus” in “Spatial Analyst Tools.”

(4) Volume of erosion and deposition: Erosion volume and deposition volume are calculated by “Surface volume” in “3D Analyst Tools.”

(5) Area of erosion and deposition: Raster data is reclassified to count the grid number of erosion and deposition. Multiply the grid number by the area of each raster to get the total area of erosion and deposition.

Results and Discussion

Coastline Temporal-Spatial Evolution Process

From the 1960s to 1990s

Total coastline length of Sanmen Bay presented a decreasing tendency from the 1960s to the 1990s. In the 1960s, the total coastline length was 476.61 km. Where artificial coastline length was 186.74 km, accounting for 39.18%, and was mainly artificial revetment and ebb dyke between farmland, pond, and tidal flat. Natural coastline length was 289.87 km and was mainly bedrock distributed at Xieqian Harbor and south of Jiantiao Harbor.

In the 1990s the total coastline length was 389.72 km, which decreased by 18.23% compared with that in the 1960s. Human activities, including...
construction of embankments and culture ponds and the reclamation project were the dominant factors to influence coastline change. South of Xiangshan County, due to the construction of culture ponds and ebb dykes, islands were turned into inland, leading to the mainland coastline length decreasing and the coastal zone area increasing. In southern Ninghai County, Huchen Harbor was turned into the inland Huchen Reservoir after the 1990s due to water conservancy construction, and the mainland coastline length decreased significantly. Artificial coastline and natural coastline in the 1990s were 174.31 km and 215.41 km, respectively, and both decreased compared with length in the 1960s.

Fig. 2. Coastline distribution maps of Sanmen Bay in the 1960s and 1990s.

From the 1990s to 2007

In 2007 total coastline length was 373.13 km, which had decreased by 4.26% compared with that in the 1990s and did not appear to be much different. The coastline showed the trend of moving toward the outside region of the bay and changed significantly in the south of Sanmen County and in the north of Ninghai County. As shown in Fig. 6, in the 1990s two islands did not belong to the mainland. The northern island was Shepan, which was the largest island in Sanmen County. In 1992, Shepan village was established and was connected

Fig. 3 Coastline comparison map of the 1960s and 1990s.

Fig. 4. Coastline distribution map of Sanmen Bay in 2007.
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with the mainland gradually to be a peninsula due to reclamation projects. The southern island was Huagu, which was the second largest island in Sanmen County. In 1992 this island belonged to the town of Liuao and was connected with the mainland gradually due to mudflat aquaculture development. However, multiple culture pond construction inside gulfs from the 1990s to 2007 led to the curving natural or artificial coastline becoming straight artificial coastline, which contributed to the total coastline length decreasing.

The artificial coastline in 2007 was 262.61 km, which had increased significantly compared to the 1990s, and accounted for 70.38% of total coastline length.
The natural coastline was just 110.52 km, and mainly existed in Xieqian Harbor and south of Jiantiao Harbor.

**From 2007 to 2011**

The total coastline length of Sanmen Bay in 2011 was 379.27 km, and it did not appear to be much different compared with that in 2007. The coastline change mainly occurred in the south of Ninhai County. This area was Xiayangtu in 2007, the largest tidal flat resource in Ninhai County, and was classified as part of Changjie town in 2011. The Xiayangtu reclamation project was a priority project of Zhejiang Province. The preliminary work had been launched officially at the beginning of 2007 and the project was fully completed in January 2013. As shown in Fig. 9, in 2011 Xiayangtu was classified as part of the mainland, but the level of land exploitation and utilization was still low.

Artificial coastline in 2011 was 271.82 km, increased by 3.51% compared with that in 2007. While the natural coastline was 107.45 km and decreased by 2.78%. In the meantime, the proportion of artificial coastline continued to grow and increased to 71.67% in 2011.

**From 2011 to 2015**

The total coastline length of Sanmen Bay in 2015 was 423.11 km, which increased by 11.56% compared with that in 2011. The proportion of artificial coastline continued to grow and increased to 77.41% in 2015. From 2011 to 2015, the coastal zone area just increased by 10.57 km², and did not appear to be much different. The reclamation projects mainly occurred in Hairun.

![Fig. 9. Remote sensing image comparison map of 2007 and 2011.](image)

![Fig. 10. Coastline distribution map of Sanmen Bay in 2015.](image)

![Fig. 11. Coastline comparison map of 2011 and 2015.](image)
subdistrict and Shepan village of Sanmen County, and the town of Xinqiao in Xianshan County.

Change Rate Analysis of Coastline Length

The total coastline length of Sanmen Bay first decreased and then increased during the last 50 years. The most obvious change of total coastline length occurred from the 1960s to the 1990s. Man-made embankments, culture ponds, and water conservancy projects significantly influenced coastline change. However, from the 1960s to the 1990s the natural coastline had the higher percentage and the slower change rate. The total coastline length decreased by 2.56 km a year.

After the 1990s, with artificial interference gradually increasing, the coastline experienced a change process of the curving coastline, becoming a straight coastline and moving outward continually. The total coastline length also first decreased and then increased. Although the variation is small, spatial form of the bay changed significantly. Shepan and Huagu islands connected with the mainland as part of the Xiayangtu reclamation project, and coastline changes in Xieqian Harbor were due to manual work on coastline form in the short term. The total coastline length change had the fastest rate from 2011 to 2015, increasing 10.96 km a year. After 2007, artificial coastline accounted for more than 70%. The natural coastline was just 95.6 km in 2015. The influence of manual work on coastline was more and more pronounced.

Table 2. Coastline change rate analysis (km/a)

<table>
<thead>
<tr>
<th>Time</th>
<th>Total coastline length</th>
<th>Artificial coastline</th>
<th>Natural coastline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960s-1990s</td>
<td>-2.56</td>
<td>-0.37</td>
<td>-2.19</td>
</tr>
<tr>
<td>1990s-2007</td>
<td>-1.84</td>
<td>9.81</td>
<td>-11.65</td>
</tr>
<tr>
<td>2007-2011</td>
<td>1.54</td>
<td>2.30</td>
<td>-0.77</td>
</tr>
<tr>
<td>1960s-2015</td>
<td>-1.05</td>
<td>2.76</td>
<td>-3.81</td>
</tr>
</tbody>
</table>
tidal flats, such as Baijiao Channel and Qingshan, Liyang, Qimen, and Haiyou harbors. A multistage branching stream embedded inland and alternated arrangement with lingulate tidal flats. The tide flats were wide and the isobaths were sparse in Qingshan, Liyang, Qimen, and Haiyou harbors, where there was relatively simple underwater topography. The isobaths of Jiantiao Harbor and Baijiao Channel were dense and deep into the mainland. The deepest isobaths of these two places were 20 m and 30 m, respectively, and the underwater topography was steeper. Shepan, Manshan, and Maotou channels were connected with Qingshan, Liyang, Qimen, and Haiyou harbors, and had complex underwater topography. There were many islands in this area. The isobaths gradually increased in depth outward around the island, were dense and distributed in a disorderly manner, and formed the multiple channel structure. Shipu Harbor also had complex underwater topography and a narrow tidal flat. The isobaths were distributed densely and the underwater topography was steep. There were many islands in the harbor. The deepest isobath was 30 m.

Form 1960s to 2015, coastline and 0 meter isobath showed the trend of moving outward. The bay area decreased and most channels deposited. The deepest isobath was 50 m in 2015, which exists in the south of Huao island and Gaotang island, and the east of Shipu Harbor. In general, the underwater topography in 2015 was more complex than that in the 1960s.

Variation of underwater topography erosion and deposition in Sanmen Bay is presented in Fig. 15. The deepest erosion depth from the 1960s to 2015 was 48.9 m, in eastern Shipu Harbor. The deepest deposition depth was 30.67 m, in the south of Gaotang Island. We used the surface volume tool to calculate erosion and deposition volumes from the 1960s to 2015, which were 1.95*10^8 m³ and 1.32*10^9 m³, respectively. Deposition volume was 6.8 times the erosion volume. As seen in Fig. 16, erosion areas were mainly in Baijiao Channel, Haiyou Harbor, Shipu Harbor, and the middle of Maotou Channel and Manshan Channel. In Haiyou Harbor and Baijiao Channel, the middle eroded and the two sides deposited, and the underwater topography was steeper. Shipu Harbor and the middle of Maotou Channel and Manshan Channel were multiple channel structures, and the erosion and deposition distribution was not obvious.

Erosion and deposition conditions of six main branches are shown in Table 3. From the 1960s to 2015, the deposition area of each branch was bigger than the erosion area, and deposition volumes were larger than erosion volumes besides Shipu Harbor.

Shipu had the deepest erosion depth, and the average erosion depth was 5.18 m. In addition, the region of Shepan and Manshan channels also had greater erosion and deposition depths, and unstable underwater topography. Shipu Harbor, Shepan Channel, and Manshan Channel were the route connected with open seas, influenced significantly by tide and topography. Qingshan, Liyang, Qimen, and Haiyou harbors had relatively shallow erosion and deposition depths, and a wider range of deposition. Human activity such as reclamation and dams contributed to the coastline and tidal flat moving outward gradually, promoting the tidal flat deposition, and had taken a critical role of affecting branch development in Sanmen Bay.
Conclusions

The total coastline length of Sanmen Bay first decreased and then increased over the last 50 years. The most obvious change of total coastline length occurred from the 1960s to the ’90s. However, in this period, the natural coastline had a higher percentage and slower change rate. The total coastline length decreased 2.56 km a year. After the ’90s, with artificial interference gradually increasing, the coast line experienced a change process of curving coastline becoming straight coastline and then moving outward continually. The total coastline length first decreased and then increased. Although the variation is small, the spatial form of the bay has changed significantly. Shepan and Huagu islands connected with the mainland, Xiayangtu reclamation project, and coastline change in Xieqian Harbor were the impact of manual work on coastline form in the short term. After 2007, artificial coastline accounted for more than 70%. The natural coastline was just 95.6 km in 2015. The influence of manual work on the coastline was more and more pronounced.

From the 1960s to 2015, coastline and 0 meter isobath showed the trend of moving outward. The bay area decreased and most channels deposited. In general, the underwater topography in 2015 was more complex than that in the 1960s. Form the 1960s to 2015 the deposition area of each branch was bigger than the erosion area, and deposition volumes were larger than erosion volumes besides Shipu Harbor. Human activity had a critical role of affecting branch development in the Sanmen Bay area.

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