Characteristics and Exploration of the Geomorphological Evolution of Lingdingyang Estuary in Recent Decades

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Abstract. Based on the underwater topographic data of Lingdingyang since 1970s, the new characteristics of the evolution of the swale in Lingdingyang estuarine bay were analysed and the causes of the evolution were discussed. The results indicated that the West Shoal silts eastward and southward, and its spreading speed gradually slows down after 1985. Area in the north of the West Shoal decreases gradually and the in the south of the West Shoal the shoal area increases gradually. Recently, in the north of the Middle Shoal scour occurred, while in the south silt is the primary evolution. The -5m contour line of East Shoal has little variation, and the swale surface area is also decrease gradually. The average annual erosion and deposition of the East, Middle and West Shoals of Lingdingyang has a certain correlation with the annual average sediment discharge of the main hydrological stations upstream. The correlation of the West Shoal is the best, Due to the high intensity of reclamation, the channels of in the west of Lingdingyang extends significantly to the sea. The runoff channels in the West moves downward, and the sedimentation center of the West Shoal tends to moves southward.

1. Introduction
Lingdingyang is the largest estuarine bay in the Pearl River Delta. Under the significant influence of human activities, the hydrological and geomorphic situation of Lingdingyang has undergone great variations [1]. The existing researches mainly focused on the characteristics of water and sediment and the evolution of swale pattern, but most of them are the research results before 2000, and mainly focused on the evolution characteristics of inner Lingdingyang [2-9]. However, relatively rare research focuses on geomorphic situation of Lingdingyang and the erosion and deposition conversion between inner and outer Lingdingyang. In recent 30 years, under the influence of human activities, the Pearl River Network watercourses cut down, the development at the mouth of the Pearl River has slowed down, local flood disaster, saltwater tide upstream, dike instability, and the potential risks of shoreline erosion have increased. Under dualistic effects of natural and artificial, the recent evolution characteristics of Lingdingyang, the erosion and deposition conversion among geomorphic units, and the main factors affecting the erosion and deposition changes of Lingdingyang are worthy to be studied in-depth, which have instructive significance for the Pearl River estuary regulation.

Lingdingyang is the most important estuary of the Pearl River Estuary, which located in the east of the Pearl River Estuary (113°33′-114°09′E, 22°12′-22°45′N). Lingdingyang estuary originated from
Humen in the north with a width of 4km, appeared a trumpet shape to Hongkong-Macao in the south with a width of 60 km, and stretches 65 km in length from the bay top to the bay mouth. The Lingdingyang stretches from NNW to SSE, and its topography inclines from the bay top to the bay mouth, which is narrow in the north and wide in the south. The underwater topography is deep in the east and shallow in the west and stretches southern like of a funnel. There are four estuaries in Lingdingyang from north to South: Humen, Jiaomen, Hongqimen and Hengmen, among which Humen is tidal estuary and the other three are runoff estuary [10]. Under the joint action of the runoff and tidal at the fourth estuary in the East, a special pattern of “three shoals (West Shoal, Middle Shoal and East Shoal) two troughs (Lingding Channel and East Channel)” was formed (shown in figure 1). Since the 1980s, the Lingdingyang has undergone various high-intensity development activities, such as large-scale land reclamation, port and watercourse construction, and upstream reservoirs, etc., which have greatly changed the water and sediment conditions and evolution characteristics of the Lingdingyang.

![Figure 1. The Lingding Bay estuary.](image)

2. Materials and Methods
The topographic data of this study sourced from the historical charts or underwater elevation maps of Lingdingyang in 1977, 1985, 1999 and 2011, respectively, the hydrological data mainly include the annual average runoff and sediment discharge data of Sanshui, Makou and Boluo stations since 1970 s, and the remote sensing images mainly include Landsat series and domestic high-resolution satellite images of the Pearl River estuary since 1970 s with resolutions ratio of 30 m and 15 m respectively. The main research methods are expressed as follows: (1) Digitize the sea-chart and topographic map to get the underwater terrain elevation data and unify the elevation base plane and coordinate system. (2) Based on ArcGIS software, Kriging interpolation method was applied to interpolate the underwater terrain elevation data to generate digital elevation model (DEM). (3) Based on DEM data of various years, contour lines were extracted and compared to analyse the change of swale pattern in the estuary, DEM data were used for elevation superposition analysis, the volume of Lingdingyang and the erosion and deposition variation were calculated according to the geomorphic characteristics, and the erosion and deposition variation maps during various periods were generated to understand the temporal and spatial distribution characteristics of erosion and deposition in Lingdingyang. (4) The ENVI software
was applied for geometric correction of remote sensing satellite images. The coastline over the years was extracted according to the corrected images, and the shoreline variations of Lingdingyang were analysed by superposition and comparison.

3. Analysis of Erosion and Deposition Evolution in Lingdingyang

3.1. Plane Change

The variation of -3 m, -7 m, -10 m contour lines in Lingdingyang from 1977 to 2011 is shown in figure 2 and table 1. The West Shoal is continuously silting to the east and south, and its spreading speed gradually slows down recently. At section X5, situated in the north of West Shoal, the advancing speed of the -3 m contour line is 0.141 km/a before 1985 to the southeast (the location of the section is shown in figure 2) and about 0.083 km/a after 1985. At section X2 and X3, the average eastward spreading speed of -3 m contour line in the middle section of West Shoal is 0.029 km/a from 1970 to 1985. From 1985 to 1999, the eastward spreading speed for the two sections is 0.026 km/a and 0.034 km/a, respectively. After 1999, the spreading speed is -0.054 km/a and -0.011 km/a for two sections, respectively, which indicated the erosion of the shore. At section X7, situated in south of West Shoal, the spreading speed of -3 m contour line has a decreasing trend. From the view of change of the shoal area, the area of the shoal in the north decreases gradually, while increases gradually in the south.

![Figure 2. The contour comparison in 1977-2011.](image)

Table 1. The speed of Scour for the shallow beach of Lingding Bay in 1977-2011 unite: m/a.

| Section | 1977-1985 | 1985-1999 | 1999-2011 |
|---------|-----------|-----------|-----------|
| X1      | 126       | 83        | 62        |
| X2      | 104       | 50        | 41        |
| X3      | 9         | 9         | 37        |
| X4      | 13        | -12       | -33       |
| X5      | 21        | -33       | -7        |
| X6      | -16       | 8         | 31        |
| X7      | -21       | -5        | 15        |

On the whole, the Middle Shoal continues to be silted to the southeast. A new deep trough with depth of -7 m is formed in the middle and upper of the Middle Shoal, and the area of shoal decreases
obviously at -7 m. From 1970 to 1985, the -7 m contour line of the Middle Shoal expanded to the east and south, and the Middle Shoal increased by 68.10 km² during this period. From 1985 to 1999, the blocking-river sand tail in the Middle Shoal and the Fanshi Shoal retreated obviously. Due to the channel excavation, the Fanshi Shoal in the southeast of the Middle Shoal was disconnected from the Tonggu Shoal, and the shoal area was reduced by 3.84 km². After 1999, the eastward spreading speed of the Middle Shoal slowed down obviously, while the northern shoal was reduced to a great extent under the action of sand excavation. By 2011, a new -7 m deep trough (hereinafter referred to as “the Middle Trough”) appeared in the middle and upper part of the Middle Shoal, which led to the separation of blocking-river sand tail and Fanshi Shoal in the Middle Shoal, and the shoal area was further reduced.

The -5 m contour line of East Shoal has little change on the plane, and the area of East Shoal decreases gradually. Since 1970, the -3 m and -5 m contour lines of East Shoal have been basically stable with some local parts slightly retreated. However, due to the influence of a series of development projects in the east of Lingdingyang, the eastern coastline is constantly advancing to the sea, and the shoal surface of the East Shoal decreased gradually, shown in table 2.

Table 2. The changes of Lingding Bay shallow beach area in 1977-2011 unite: km².

| Zone                  | 1977-1985 | 1985-1999 | 1999-2011 |
|-----------------------|-----------|-----------|-----------|
|                       | Increased area | Increased area | Increased area |
| Jibaosha-Longxue island | 10.70     | 2.02      | -3.88     |
| Wanqingsha Shoal      | 23.22     | 7.18      | 0.95      |
| Hengmen-Qiao Shoal    | 12.58     | 14.47     | -1.2      |
| South of West Shoal   | 17.18     | 13.55     | 7.93      |
| Middle Shoal          | 68.10     | -3.84     | -6.7      |
| East Shoal            | -5.64     | 2.13      | -0.05     |

Viewed from the change of the deep trough, the position of the West Trough keeps basically stable, the width of the trough extends to both sides, the -10m contour line runs through the whole line, and forms a smooth west channel, which is related to the widening and dredging of the West Trough since 1984. There is no significant change in the plane of the East Trough, and the water depth of the lower section near Chiwan and Mawan of the western port area of Shenzhen has increased.

3.2. Erosion and Deposition Changes

By taking the -5 m contour line as the boundary of shoal (-7 m as the boundary of the Middle Shoal) and the water zone with -10 m water depth as the boundary of deep trough, the erosion and deposition change speed and the change of swale volume for the main geomorphic units were calculated respectively according to the underwater topographic data, shown in table 3.

Table 3. The statics of volume variation for different geomorphic units of Lingding Bay in 1977-2011 unite: 10⁶ m³.

| Year      | Masha Shoal | Hengmen tail Shoal | Wanqingsha Shoal | Qiao island south Shoal | Middle Shoal (North) | East Shoal | Deep Trough (East-West Trough) |
|-----------|-------------|--------------------|------------------|-------------------------|----------------------|------------|-------------------------------|
| 1977-1985 | 9.17        | 29.82              | 39.29            | 5.22                    | 26.82                | 6.58       | -51.47                        |
| 1985-1999 | 12.08       | 0.2                | 8.9              | 9.69                    | -7.68                | -7.24      | -144.02                       |
| 1999-2011 | 3.68        | 5.76               | -21.39           | 5.9                     | 16.03                | 23.96      | -326.79                       |

a Positive refers to silting, negative refers to scouring.
b Statistical ranges are shallower than -5 m, shallow than -7 m, deeper than -10 m for East and West Shoals, Middle Shoals, and deep troughs, respectively.
Under the natural evolution state, the West Shoal presents the characteristics of “shoal silting and trough erosion”. Recently under the condition of frequent human intervention, the local shoal surface of the West Shoal is scoured, and the eastward spreading speed of the shoal slows down. From 1977 to 1985, the evolution of swale was natural evolution mainly with the average deposition speed of was 4.3 cm/a, and the maximum siltation intensity zone was located in the south of West Shoal with the speed of 8.2 cm/a. After 1985, due to the decrease of sediment inflow from upstream and the increasingly frequent of human activities such as sand excavation, the deposition speed of shoal decreased to 1.3 cm/a, and the zone with the maximum siltation intensity was still located in the south of the West Shoal with a speed of 3.8 cm/a.

The Middle Shoal silted in the east and scoured in the west. Generally, the deposition of the shoal eastward slowed down and scoured at some local zones. From 1977 to 1985, the Middle Shoal silted with the average deposition speed of 3.7 cm/a in the north and south. After 1985, with the deepening of the West Trough of Lingdingyang, the tidal force upward increased, and the west side of the Middle Shoal was continuously scoured by tidal force. From 1985 to 1999, the Middle Shoal scoured mainly. Recently the north of the Middle Shoal scoured, and the south silted, which indicated that the sedimentary center of the Lingdingyang shifts from the middle and upper to the south.

In the early stage the erosion and deposition kept a relatively balance in East Shoal, and recently slight deposition. From 1977 to 1999, the East Shoal was in a relatively balanced state with a change range of ±1 cm/a. From 1999, the East Shoal has been in a silting state. From 1999 to 2011 the average siltation speed is 10 cm/a. Recently, the deposition increased in the East Shoal, which is related to the increase of sediment distribution ratio of Fuzhou channel after the regulation of western entrance, and more water and sediment are discharged into Chuanbi channel through Fuzhou channel and then into eastern Lingdingyang water zone.

The East Trough and West Trough are in the state of undercutting and deepening. The East and West Troughs were scoured and silted before 1985. Afterward, the trough was cut deeper due to the channel excavation. From 1985 to 1999, the average erosion speed of the West Trough was 14.51 cm/a. From 1999 to 2011, the West Trough was further undercut with an average annual deepening speed of more than 30 cm/a. From 1985 to 1999, the East Trough was in a state of erosion with the erosion speed between 2.5 and 10 cm/a, shown in figure 3(b). From 1999 to 2011, obvious undercutting occurred in local East Trough due to sand excavation, with the undercutting depth of 4.51-7.50 m.

Figure 3. (a) The scouring speed of Lingdingyang in 1977-1985. (b) The scouring depth of Lingdingyang in 1985-1999 (m). (c) The scouring depth of Lingdingyang in 1999-2011 (m).
4. Exploration of Erosion and Deposition in Lingdingyang

4.1. Erosion and Deposition Change and Reservoir Construction

Since the 1990s, large-scale reservoir construction began in the upper reaches of the Pearl River, and the reservoir projects put into operation reached the peak in early 2000. The reservoir capacity in the upper reaches of Xijiang River was $142.79 \times 10^8$ m$^3$ at the end of 1999 and increased to $635.72 \times 10^8$ m$^3$ in 2004 [11]. The reservoir can intercept a large amount of sediment in the basin, and the average annual sediment flux in the Pearl River Basin has decreased from more than 87 Mt in 1980s to less than 32 Mt in 2000s. The correlation between the annual average erosion and deposition of the East, Middle and West Shoals of Lingdingyang and the sum of the annual average sediment discharge at Sanshui, Makou and Boluo stations is shown in Table 4. The correlation coefficient between the scouring and silting amount of the West Shoal and the average annual sediment discharge of the three upstream stations is relatively high. With the decrease of the sediment discharge, the sedimentation amount gradually decreases, and the change is shown in Figure 4. The correlation coefficient between the scouring and silting amount of the Middle Shoal is positive, with the correlation coefficient of 0.78, while the correlation between the East Shoal and the cumulative sediment discharge and incoming sediment coefficient is poor, which is mainly due to the obvious influence of tidal on the East Swale. The change of erosion and deposition is not only affected by the upstream water and sediment, but also by the comprehensive influence of tidal sand transportation, which leads to the poor correlation between the East Swale and the upstream cumulative sediment transport and sediment coefficient.

**Table 4.** Statistics of correlation coefficient between total amount of incoming sediment and incoming sediment coefficient and erosion and deposition.

| Relationship       | Coefficient between total amount of sediment and erosion and deposition | Coefficient between sediment coefficient and erosion and deposition |
|--------------------|------------------------------------------------------------------------|-------------------------------------------------------------------|
|                    | East Shoal | Middle Shoal | West Shoal | East Shoal | Middle Shoal | West Shoal |
| Correlation coefficient | -0.45      | 0.78       | 0.97       | -0.69      | 0.60       | 0.98       |

**Figure 4.** Correlation between erosion and deposition of West Lingdingyang shoal and sediment discharge of Makou, Sanshui and Boluo stations.
4.2. Shoal Change and Beach Reclamation

Based on the comparative analysis of satellite remote sensing images, large-scale reclamation has been carried out in Lingdingyang since 1970s, shown in figure 5. From 1978 to 2014, the total reclamation zone of Lingdingyang is about 250 km$^2$. The zone with severe shoreline change is mainly concentrated in the west of Sankoumen, which is caused by the agricultural reclamation before 1995, such as shoal reclamation outside Jiaomenkou and Hengmenkou. The total reclamation zone in the west of Lingdingyang is about 172 km$^2$, and the shoreline spread speed seaward is 43.67 m/a. The reclamation water zone in the east of Lingdingyang is 78 km$^2$, and the shoreline spread speed seaward is 35.04 m/a. The statistics of shoal reclamation in Lingdingyang is shown in table 5. It can be seen from table 5 that since 1970 the area of Lingdingyang shoal has been increasing. However, due to the influence of reclamation, the area of shoal is decreasing. Before 1985, the intensity of shoal reclamation was less than the shoal silting speed, and the shoal area appeared a net growth state with a net increase of about 85.83 km$^2$. After 1985, the intensity of shoal reclamation exceeded shoal silting speed to a great extent with the net reduction of about 138.28 km$^2$.

Table 5. Change of reclamation area in Lingdingyang since 1977.

| Area                        | 1977   | 1977-1985 | 1985-1999 | 1999-2011 |
|-----------------------------|--------|-----------|-----------|-----------|
| Shoal area                  | Reclamation area | Reclamation area | Reclamation area | Reclamation area |
| Jibaoshan-Longxue island    | 96.13  | 3.31      | 30.64     | 7.27      |
| Wanqingsha tail Shoal       | 142.44 | 15.40     | 26.54     | 0.00      |
| Hengmen-Qiao Shoal          | 204.49 | 17.12     | 44.60     | 19.53     |
| South of West Shoal         | 37.12  | 0.00      | 1.42      | 3.14      |
| Middle Shoal                | 169.03 | 0.00      | 0.00      | 0.00      |
| East Shoal                  | 142.13 | 4.48      | 14.62     | 23.08     |

Figure 5. Shoreline change of Lingdingyang from 1978 to 2014.
4.3. Move Southward of the Sedimentation Center and the Extension of the West Sankoumen
The continuous reclamation has changed the western shoreline of Lingdingyang. Jiaomen and Hengmen in the west of Sankoumen form the swale pattern of “one main one branch”, and the trough extends into the sea significantly. From 1978 to 2014, the Fuzhou Trough and the southern branch of Jiaomen extend 4.5 km and 18.5 km, respectively. The northern and southern branches of Hengmen extend 4.3 km and 9.4 km, respectively. The Hongqili outlet extends 7.3 km to the sea. When the trough of the above-mentioned section pushed into to the outer sea, the riverbed is undercut obviously. The downward movement and deepening of the deep trough in the mouth section makes the runoff dynamics in the west move downward, which results in the deposition in the north of the West Shoal slow down. The siltation intensity of the Middle Shoal and South Shoal is greater than that of the North Shoal. The sedimentation center of the West Shoal is shifted to the south. From 1977 to 1985, the West Shoal sedimentary center was located at the end of Wanqingsha shoal, moved southward to the south of Qiao Island from 1985 to 1999, and moved to the east of Macao in 2011, as shown in figure 3.

4.4. Undercutting of East Trough and West Trough and Trough Dredging
The cutting of the East Trough and West Trough is closely related to the dredging of Lingdingyang. In the early 1990s after the West Trough was determined as the main trough of Guangzhou port, three channel dredging projects were performed, which leads to the trough bottom elevation was dredged to -17 m and the average undercutting depth of the West Trough is about 6m. In the East Trough, the seabed of the Fanshi Trough is generally 5-10 m with the maximum depth of 17 m due to the artificial seabed mining and dredging. During 2007-2008, affected by the construction of public channel in the western port zone of Shenzhen, the seabed in the lower section of the East Trough was cut down significantly, with the cutting magnitude of Mawan to Shekou mostly within 5m, and the depth of seabed near the entrance of Dachan port zone exceeded 10 m [12].

5. Conclusion
(1) After 1985, the spreading speed of the West Shoal gradually slowed down with the average deposition speed decreased by nearly 70%. The northern area of the West Shoal gradually decreased, and the southern area gradually increased. The Middle Shoal continued to be silted in the southeast direction on the whole, and the area of the shoal at -7 m decreased obviously. Recently, the north of the Middle Shoal was scoured, and the south was mainly silted. The -5 m contour line of East Shoal has little change on the plane, and the Shoal surface is also decreasing gradually.

(2) The plane position of the East Trough and West Trough keeps stable. In the vertical direction, there was erosion and siltation before 1985. After that, due to the channel excavation, the channel undercutting was deepened obviously.

(3) There is a certain correlation between the average annual erosion and deposition of the East, Middle and West Shoal of Lingdingyang and the sum of the average annual sediment discharge of Sanshui, Makou and Boluo stations in the upstream. The correlation of the West Shoal is the best, followed by the Middle Shoal, and the East Shoal appears a negative correlation.

(4) At present, the Lingdingyang shoal is still silting up, but the area of the shoal is decreasing due to the influence of reclamation. Before 1985, the intensity of shoal reclamation was less than the speed of shoal silting, and the net increasing area of the shoal is 85.83 km². After 1985, the intensity of shoal reclamation exceeded the silting speed to a great extent, which leads to the shoal area decreased by 138.28 km².

(5) Due to the continuous reclamation, the in the West Shoal of Lingdingyang extends significantly to the sea, the runoff dynamics of the west of Sankoumen moves down, and the spreading scope of the sediment southward is enlarged. As such, the deposition in the north of the West Shoal is slowed down, the sedimentation intensity in the Middle Shoal and South Shoal is greater than that in the North Shoal, and the sedimentation center of the West Shoal tends to move southward.
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