Estuary shifting and the impacts on coastline changes in the yellow river delta

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Abstract. The Yellow River Delta is a relatively new and dynamic land covered an area about 5400km². The estuary channel has shifted significantly due to high sediment availability and thus resulting riverbed aggradations. The shifting of the estuary always follows a natural and cyclic process in four steps, including, riverbed aggradations, river channel migration, channel meandering, and course change at the end. The shifting scope of the estuary covered the whole delta area. After course changing, a large sand mouth is formed projecting into the sea, and a small bay is created between two of the river mouths. The coastline of the Yellow River delta is a tortuous line that connects six large sand mouths, and the total length is about 300km. The coastline of the delta is dynamic in two areas, one is in coastline extension or land-making at the present river mouth due to a large quantity of sediment, the other is coastline erosion near abandoned river mouths due to lack of sediment replenishment, unstable deposited soil and high tidal erosion. The main objective of this paper is to elaborate the process of estuary shifting and coastline change, present an analysis of land progradation and erosion rate, and the relationship between total sediment quantity and coastline change.

1. Introduction to the delta
The Yellow River Delta is a relatively new and dynamic land formed from 1855 onward, when the Yellow River breached at Tongwaxiang (Henan Province), diverted the course from the Huai River to the Daqing River, flowed into the Bohai Sea, and then formed an fan-shape alluvial plain of 5400 km²(Figure1). During a very long period before the river changing to its current course, there had been no embankments along the channel and the river changed its course freely across the deltaic area. The river channel of the estuary has shifted at least ten times across a large area, three of which are man-made changing in 1953, 1964 and 1976 in order to avoid flooding and property losses (Figure2).

The shifting of the estuary reach always follows a natural and cyclic process of four steps that include, riverbed aggradation, river channel extension seaward, channel migration, and course shifting, which is due to the huge quantity of sediment transported. Based on long term data, the average sediment volume delivered to the delta is 0.8 billion ton per year and the average area of land forming is about 25km² per year. The total area of new land formed from 1855 to 1996 amounts to 2400km² [1].
Figure 1. Yellow River Delta (2004)

Figure 2. Courses changes after 1855
2. Estuary evolution process and coastline conditions

2.1. The basic law of the estuary evolution process

The Yellow River is well-known as a sediment-laden river. The annual averaged delivery of sediment through Sanmenxia is approximately 1.6 billion ton with sediment content of 35kg/m³. The average sediment delivered to the delta is 0.8 billion ton per year with average sediment content of 25kg/m³[2].

In estuaries area, the ocean dynamics is pretty weak with a tidal range of about 1 m in general and the area has weak sand-laden flow. Among the 1.6 billion tons of normal annual sediment flowing into the lower reaches of the Yellow River, 400 million tons is deposited into the downstream riverbeds, and the rest 1.2 billion tons in the estuaries area, of which 400 million tons is transported to the deep-sea, 800 million tons is silted up in littoral zone below Lijin, resulting in aggradations of land and further extension of the estuary. Along with the extension of the estuary and channel reach, sedimentation occurs in the upper stream channel, which causes the rising of flood level in case of the same water flow. When the flood level is higher than the ground elevation, the ocean inlet flow path will divert, therewith a river migration would be taken place.

2.2. Coastline conditions of the Yellow River Delta

The estuary reach of the Yellow River has shifted its course 10 times after the river diverted to the Daqing River and entered the Bohai Sea in 1855. Initially the river entered the sea at the northeast of the delta, and after that the course changed to the southeast, then to the north, and at present the estuary is at the east of the delta. The shifting range of the estuary reach has covered the whole delta area. When the course changes, large sand mouth projecting to the sea is formed, and a small bay is created between two of the river mouths.

The coastline of the delta changes under scour and aggradations of the Yellow River. The stability of the coastline is impacted by water and sediment volume, changing course of the estuary reach and ocean dynamics. The coastline across the estuary develops due to deposition of river sediment. The annual land progradation rate is from a few to tens of km² in a fan-shape and the deposition range is normally within 25 km of both sides of the estuary [3].

After course changing, intensive coastline erosion would occur due to lack of sediment replenishment and ocean dynamics near the abandoned estuary in the initial few years, and then the erosion rate slows down and reaches a relatively stable condition thereafter.

3. Coastline change: extension and erosion

3.1. Land progradation

The Yellow River has been present on the delta for more than 100 years, and the area of the delta in modern times has greatly increased. From statistics, the river has been present on the modern delta for 64 years from 1855 to 1954. It migrates and breaches frequently, and the total land progradation area is 1510km², averaged up to 23.6km² annually [4].

After 1954, the area over which the river in the modern delta has migrated has decreased, and three large scale course changing episodes were happened at Shenxiangou course in 1954, Diaokouhe course in 1964 and man-made course in 1976 (Figure 3). During the time from 1954 to 1976, the total land-making area is 651 km², the erosion area beyond the river mouth is 102km², and the net land-making rate is 24.9km², closing to the rate before 1954 (Table 1).

In 1976, the river shifted the course to Qingshuigou by man-made engineering. From then on, many measures were carried out to keep the course stable, and no significant channel migration occurred in the terminal reach. Land development due to sedimentation in the delta is mainly distributed along the Qingshuigou course over 20 km distance. The net land area extension in the initial several years is very fast, up to 25.9km² each year, due to the presence of a distributions channel. After 1980, the main channel was formed and kept relatively stable, net land aggradation slowed down to 15.1km² each year. After 1992, the total volume of water and sediment reaching the estuary
decreased due to climate change and water diversion in the river’s upper reaches, makes velocity decreased and caused silting in the river mouth, then a planned man-made channel adjustment had to be done in 1996 (Figure3). The land aggradation rate in this period decreased to 9.5km² each year (Table 1).

![Figure 3. Course changing after 1954](image)

**Table 1. Land aggradation conditions in the Yellow River delta.**

| Period (year) | Land aggradation area (km²) | Erosion area (km²) | Net land aggradation area (km²) | Net land change rate (km²/yr) |
|--------------|---------------------------|-------------------|-------------------------------|-------------------------------|
| 1855-1954    | 1510                      | 23.6              |                               |                               |
| 1954-1976    | 651                       | 102               | 549                           | 24.9                          |
| 1976-1980    | 179                       | 69                | 110                           | 25.9                          |
| 1980-1992    | 358                       | 175               | 183                           | 15.1                          |
| 1992-2000    | 90                        | 14                | 76                            | 9.5                           |

**3.2. Coastline extension**

The general situation of the coastline change in the delta is that coastline reaches near the current river mouth have aggraded, whereas reaches near the abandoned river mouth have experienced erosional recession, but the total sedimentation is always more than erosion due to continuous sediment replenishment [5].

The analysis of the coastline extension rate is based on measured hydrological data and the comparison of seaward advancing position of the cotidal line, 2m and 5m depth contours. Table 1 shows the extension space of each sand mouth in different periods. It is seen that the coastline advances as a whole before 1954, and the subsequent three sand mouths extend with rates of 2.59 km/yr, 2.68km/yr and 1.9km/yr respectively in this period. Table 2 shows the changing condition of the cotidal line and 2m and 5m depth contours of the Qingshuigou course after 1976. Table 3 shows the extension distance and affected coastal width of the Qingshuigou river mouth on cotidal line, 2 m and 5m depth contour after 1976.
Table 2. Coastline extending at river mouth

| Period(yr) | Chezigou mouth | Diaokouhe mouth | Shenxiangou mouth | Qingshuihou mouth | Tianshuihou mouth |
|------------|----------------|-----------------|-------------------|-------------------|-------------------|
| 1855-1954  | 16.4           | 13.0            | 21.1              | 29.7              | 23.0              |
| 1954-1963  | 27.0           |                 |                   |                   |                   |
| 1963-1976  | 33.0           |                 |                   |                   |                   |
| 1976-1995  |                |                 |                   |                   | 38.0              |

Table 3. River mouth extending at the Qingshuigou course

| Period(yr,m) | Cotidal line | 2m depth contour Extending space | Affecting width | 5m depth contour Extending space | Affecting width |
|--------------|--------------|---------------------------------|-----------------|---------------------------------|-----------------|
| 1976.05-1979.10 | 18.0         | 7.8                             | 42              | 5.0                             | 42              |
| 1979.10-1992.10 | 17.2         | 19.0                            | 36              | 15.0                            | 48              |
| 1976.05-1992.10 | 35.2         | 21.1                            | 42              | 17.0                            | 50              |
| 1992.10-1995.10 | 3.0          | 5.5                             | 20              | 6.2                             | 20              |
| 1995.10-2000.10 | 12.0         | 5.2                             | 12              | 4.9                             | 13              |
| 1992.10-2000.10 | 8.6          | 3.7                             | 24              | 6.3                             | 28              |

3.3. Coastline erosion

Land erosion is happened along most of the coastline of the delta except for the present estuary. Erosion can be described by field investigation and the depth contour change in the littoral region [6].

According to the analysis of field investigation and measurements, serious land erosion happens in the estuary coastline after the Shenxiangou course (1954-1964) and Diaokouhe course (1964-1976) stopped water and sediment transportation. During the period 1976-1980 at the Diaokouhe mouth, the 2m depth contour eroded 2km landward and the erosion rate was up to 0.5km/yr. After 1980 the erosion decreased gradually and the 2m depth contour advanced 4km landward till 1992, averaging 0.33km change annually, and the erosion space is 3km during 1992-2000, close to the rate of 1980-1992. Thus, the erosion rate of the abandoned course is much greater in the initial period.

The analysis of the erosion rate of the delta coastline is based on the change of the 2m and 5m depth contours. But the erosional extent of the sea waves on the coast is much greater, so the real erosion rate of the coastline is bigger than the 2m and 5m depth contour’s erosion rate.

Table 4. Comparison between sediment volume and coastline extending distance

| Period (yr,m) | Sediment volume (b ton) | Extending distance (km) | Running ages (yr) | Extending rate (km/yr) | Sediment extending space (km/0.1b ton) |
|---------------|-------------------------|-------------------------|------------------|------------------------|---------------------------------------|
| 1953.07-1963.12 | 12.97                   | 27                      | 10.4             | 2.59                   | 0.21                                  |
| 1964.01-1976.05 | 13.46                   | 33                      | 12.3             | 2.68                   | 0.25                                  |
| 1976.06-1996.06 | 12.82                   | 38                      | 20.0             | 1.90                   | 0.30                                  |
| 1996.07-2000.10 | 1.02                    | 12                      | 4.25             | 2.82                   | 1.17                                  |
3.4. The relationship of coastline change and water-sediment condition

The coastline evolution of the delta is determined by the amount of water and sediments that reach the estuary and the affected area is mainly concentrated near the river mouth. Table 4 shows the comparison between sediment volume carried to delta and the extending distance of the river mouth.

From the table it can be discovered that the coastline extending space per 0.1 billion ton sediment near river mouth has no significant difference during the first two periods (Shenxiangou course and Diaokouhe course). The reason is the water depth and sea dynamics near two river mouths are similar, and the river’s water and sediment condition is relatively stable during the two periods. The sediment extending space in the third period (Qingshuigou course) is somewhat bigger due to shallow sea water depth near the river mouth and weak sea dynamic conditions. After the man-made changes in the Qingshuigou course, the sediment extending space is significantly bigger than before. There are two main reasons for this change, one is the water depth near estuary area is very shallow in the initial several years, another is that the river mouth is stable after geoengineering leading to rapid coastal progradation.

From the analysis above it can be concluded that, for the river mouth, 0.1 billion ton sediment can cause 0.2-0.3km extension to the sea, and the rate also depends on the total annual sediment volume. If the annual sediment volume is less than approximately 0.1 billion ton, coastline extension would not happen and even net erosion would occur.

4. Conclusions

According to the analysis of coastline change based on annual monitoring data, the general changing situation of the delta coastline is as follows:

The reaches at the west of the abandoned Diaokouhe mouth is stable after two periods’ erosion;

The reaches from the east of the abandoned Diaokouhe mouth to the artificial outlet is stable, protected by a standard sea dike;

The present river mouth, the artificial outlet, is extending and dynamic across an area of 10km range;

The reaches within 20-30km range of the abandoned Qingshuigou mouth is in the transitional stage of from high to low erosion;

The reaches at the south of the abandoned Qingshuigou mouth is in a relatively stable situation.

Coastline change near the present river mouth shows relatively fast progradation during the initial period of each river course, slows down when the mouth reaches deep water. For abandoned river mouths, the erosion rate is relatively fast for the initial period after the river course has shifted to another location, and then slows down and till relatively stable.

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