The evolution characteristics and dynamic mechanism of the mouth reach in the Yellow River Estuary

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Abstract. The Yellow River Estuary is a depositional microtidal estuary which is dominated by dynamic runoff. In the present study, based on actual measured hydrological data and remote sensing images, the evolution characteristics of the sand spit, gully, branch channels, and mouth bar of the Yellow River Estuary were analysed. It was determined that prior to 1998, the incoming flow and sediment had been large, and the deposition and extension speed of the sand spit had been relatively fast, with the mouth bar becoming highly developed. However, after 1998, the incoming flow and sediment entering the Yellow River Estuary had become significantly decreased. It was observed that erosion had occurred in the sand spit, and the mouth bar had become shrunken. Currently, there are many types of gullies and branch channels in the mouth reach area, including main channels, branch channels, flood gullies, and tidal gullies which can be transformed into each other. By establishing the relationship between the incoming sediment and the epeirogenic area, it was found that the incoming sediment level from the Yellow River Estuary of 300 million tons was the equilibrium point of the sand spit deposition and erosion, and there was an approximate linear relationship observed. The evolution characteristics of the mouth reach included two categories: persistent influencing factors and accidental influencing factors. Among those, the incoming flow and sediment were determined to be the main continuous dynamic actions, and storm surges, channel oscillations, and water-sediment regulations were considered to be accidental factors. Although the time period was short, the impacts were found to have been significant. This study’s research results potentially provide a scientific basis for the future comprehensive planning of flow path stability.

1. Introduction

The Yellow River Estuary is considered to be a depositional microtidal estuary. Large amounts of sediment are continuously carried into the Yellow River Estuary, which results in a continuous deposition and extension in the estuary area. A mouth bar has also been formed which impedes the sediment flow in the mouth area. The rise and fall of the mouth bar tend to lead to changes in the erosion datum in the lower Yellow River, which greatly affects the deposition, erosion, and flood control safety of the lower Yellow River, especially in the estuary area. In addition, it has been found that although the mouth bar in the estuary area is formed by a combination of dynamic runoff and ocean actions, for a microtidal estuary, the influences of the dynamic runoff are the main influences. In view of the major changes in the flow and sediment levels entering the Yellow River Estuary in recent years, the rapid development of the social economy in the estuary area has also been observed.
to have placed higher demands on the governance of the Yellow River Estuary. Therefore, the examination of the evolution processes and dynamic response mechanism of the Yellow River Estuary’s mouth reach under different flow and sediment variations is extremely important to ensure the sustainable development of the national economy in the area of the Yellow River Estuary.

Since 1986, the inflow and sediment conditions of the Yellow River Estuary have changed significantly. The estuary has changed from a strong deposition to a weak deposition, and the sand spit has even displayed erosion retreat conditions. Since the implementation of water and sediment regulations in the Xiaolangdi Reservoir in 2002, the occurrences of larger flow and sediment processes in the Yellow River Estuary have increased, and the probability of branch diversions in the mouth reach area has increased significantly. Therefore, in order to ensure the long-term stability of the flow path in the Yellow River Estuary, it has become necessary to analyze the evolution characteristics and dynamic mechanism of the mouth reach area following the changes in the flow and sediment in the Yellow River Estuary [1]. In accordance with the measured data of the flow and sediment processes of the Lijin Hydrological Station, the yearly cross-section topography in the estuary reach and coastal zone, TM remote sensing images of the 30 m resolution, and so on, this study analyzed the evolution such key factors as the sand spit, epeirigenous area, gullies, branch channels, and the mouth bar in the mouth reach area following the diversion of the Yellow River Estuary to the Qingshuigou flow path. Also, the constraints and main dynamic mechanisms between the aforementioned factors were analyzed. The results of this study will potentially provide technical support for the future flow path planning in the area of the Yellow River Estuary.

2. Evolution characteristics of the mouth reach area in the Yellow River Estuary

2.1. General situation of the mouth reach area

The Yellow River Estuary is located on the southwestern coast of the Bohai Sea, between Bohai Bay and Laizhou Bay, with a latitude between 37°N and 38°N. In this study, the Yellow River Estuary was divided into a tail channel reach, mouth reach, and coastal area, as shown in figure 1. The Yellow River Estuary reach generally refers to both the tail channel reach and the mouth reach. The upper boundary of the tail channel reach is the Lijin Hydrological Station. The lower boundary includes the upper boundary of the runoff tidal wave area approximately 20 km above the entrance to the sea. The mouth reach refers to the area from the uppe boundary of the runoff tidal wave area to the vicinity of a 12 m isobath on the Yellow Sea datum. Also, the mouth reach includes the runoff tidal wave area and the runoff tidal current area. The boundary point has been determined to be the stagnation point of the interactions between runoff and tidal currents. The area above the stagnation point is considered to
be the runoff tidal wave area, and the area below the stagnation point is considered to be the runoff tidal current area. The coastal area refers to the areas with depths beyond the 12 m isobath on the Yellow Sea datum. Generally speaking, the variations in the flow velocity in the tail channel reach are mainly affected by the incoming runoff and the boundary conditions. In addition to the above-mentioned factors, the flow velocities in the runoff tidal wave area are also known to be affected by the tidal fluctuations in the sea area outside the mouth area. Furthermore, in addition to the direct effects of the river runoff and tidal currents, the flow velocities in the runoff tidal current area are also known to be affected by the brine infiltration levels [2,3].

2.2. Evolution characteristics of the mouth bar

The evolution of the mouth bar generally refers to the longitudinal variations of the mouth bar along the river direction, which is composed of an upward slope reach, top slope reach, and steep slope reach, as shown in figure 2. In addition to the slope of the three reaches, the characteristic parameters which were used to describe longitudinal variations also included the length of the mouth bar along the river direction; the deposition and erosion distances; and the top elevations [4,5]. In accordance with the underwater topographical map of the coastal area in the Yellow River Estuary, the height of the bed surface was calculated along the direction of the mainstream flow into the sea. It could be seen that the change ranges of the upward slope reach, top slope reach, and steep slope reach were 0.3 to 4.4 km, 0.9 to 4.8 km, and 0 to 1.3 km, respectively. The average top elevation of mouth bar was observed to generally be between -0.8 and 0.5 m on the Yellow Sea datum. In the meantime, the mouth bar elevation was generally higher than the average bed elevation by 0.25 to 1.75 m. The slope of the upward slope reach was observed to be generally between -1/5000 and -1/100, and the changes in its value were mainly related to the incoming flow and the development stage of the mouth bar. It was found that when the incoming flow was small, or the mouth bar was in an early stage of development, the slope of the upward slope reach was steep. However, when the incoming flow was large, or the mouth bar was in a middle or late stage of development, the slope of the upward slope reach was low. The slope of the steep slope reach was found to be generally between 1/400 and 1/200. The slope of that reach was observed to be much larger than the natural slope of the coast, and its formation was determined to be mainly related to the composition of the flow and sediment in the Yellow River, as well as the ocean dynamics. Therefore, it was confirmed that when the incoming flow and sediment were large, the slopes were steeper, and when the incoming flow and sediment were small, the slopes were lower. It was found that after the river cut offs or the channels were diverted, the slopes had gradually slowed down due to the erosion of the sand spit and had eventually recovered to the natural slope degrees of the coastline.

![Figure 2. Schematic diagram of the longitudinal section in the mouth reach area.](image)

The length of the mouth bar along the river direction was determined to basically range between 6 and 10 km prior to the 1980s; 5 to 6 km from 1984 to 1992; approximately 3 km from 1993 to 1995; and 2 to 3 km since 1996. It could be seen that the length of the mouth bar along the river direction had become gradually decreased over time. Also, the top elevation of the mouth bar had increased by 0.5 m between 1984 and 1987; decreased by 0.5 m from 1988 to 1995; and decreased by 0.22 m from
1996 to 1999. The top elevation of the mouth bar had gradually decreased with the decreases in the incoming flow and sediment. The annual average deposition speed was 1.3 km/a between 1984 and 1987, and annual average deposition speed was 1.12 km/a from 1988 to 1995. Then, following the branching of the Qing-8-section in 1996, the annual average deposition speed of the new mouth reach was determined to be 0.3 km/a between 1996 and 1999, and the annual average deposition speed had been -0.45 km/a from 2000 to 2002.

2.3. Evolution characteristics of the sand spit
Sand spits are known to be important features of alluvial estuaries. The deposition and erosion of the sand spits are closely related to the changes of the coastline on both sides, and are considered to be the areas with the most dramatic epeirogenic changes in estuaries areas. According to the findings of Yang et al [6], during the more than 30-year period ranging approximately from 1976 to 2008, the sand spit of the Qingshuigou flow path had presented an overall state of deposition and extension, with a net epeirogenic area measuring 382 km$^2$ and an annual average epeirogeny area of 12 km$^2$. During the period from 1987 to 1995, the Qingshuigou flow path entered the sea in a southeast direction, and the sand spit had been extended by 15 km. At that time, the epeirogenic area measured approximately 236.4 km$^2$, and the annual average epeirogenic area was 29.8 km$^2$. In 1996, an artificial diversion was carried out on the Qing-8-section and the flow path entered the sea in a northeast direction. The initial epeirogenic speed was very fast, reaching a maximum in 1998. The river channel had extended approximately 7 km and the epeirogenic area was estimated at 25 km$^2$. However, after 1998, due to significant decreases in the incoming flow and sediment, the deposition and extension speed of the new sand spit became slower, and the old southeast sand spit had eroded and retreated under the action of the ocean dynamics, as shown in figure 3. Then, by May of 2005, the sand spit was found to have retreated 2.83 km, and the erosion area was determined to be approximately 15.8 km$^2$.

![Figure 3. Changes in the coastline near the sand spit of the Qingshuigou flow path.](image)

It was found that from an inter-annual perspective, the sand spit of the Qingshuigou flow path had changed dramatically. There were large change ranges observed in the deposition and erosion during certain one- or two-year periods, such as 1988 to 1989, 1990 to 1991, and so on. Also, the change ranges of other years were found to be relatively small. There also were large short-term change rules and small long-term change rules observed in the sand spit. The maximum range of the inter-annual deposition was found to reach more than 5 km, and there was even erosion observed when the range of the inter-annual deposition had reached the minimum. However, from the statistical results of four years or longer, the annual average deposition range was determined to be approximately 1 km.

2.4. Evolution characteristics of the gullies and branch channels in the mouth reach area
In the study area, the sand spit had not been formed at the beginning of the Qingshuigou flow path. The cecum gully formed by tidal current was mainly on the sandy beach area, and there were almost
no branch channels connected with the river near the estuary. Also, by that time, the epeirogenic speed of estuary had become very fast, and the annual epeirogenic area was observed to have reached dozens of square kilometres. However, after the formation of the sand spit, it had suffered from enhanced ocean dynamic actions due to the protruding effects of the sand spit. At the same time as the occurrences of the strong deposition and erosion, many cecum gullies had also been formed on the sand spit, and branch channels which connected with the main channel had gradually appeared. It was found that the number of gullies and branch channels had gradually increased with the passage of time. In the current study, by analysing the available remote sensing images since 1980, it could be seen that prior to 1985, there were only some small tidal gullies around the sand spit in the study area. However, after 1985, the number of tidal gullies had increased, and branch channels had also appeared. Also, there were more gullies and branch channels in the Yellow River Estuary area as a whole. The number of gullies and branch channels in 1992 was observed to be significantly higher than those observed in 1987. In 1992, after a flood season from June to October, it could be seen that the main channel had changed. In early June, the main channel which had entered the sea in the east had disappeared. It was observed to have been replaced by the original southward branch channel, as shown in figure 4. In terms of the number of gullies and branch channels, the north side was found to have more than the south side prior to 1996. Then, the south side had more than the east and north sides after 1996. The inlet direction, along with the distribution of the deposition in the shallow sea, was determined to have had major influences on the number of gullies and branch channels in the study area.

![Figure 4](image)

**Figure 4.** Evolution of the gullies and branch channels in the mouth area.

3. **Mutual influences of the different characteristic factors in the mouth reach area**

3.1. *Evolution of the sand spit and epeirogenic areas*

At the beginning of the Qingshuigou flow path diversion, the coastline near the mouth area was flared, and the sand spit had not yet formed. The epeirogenic speed was mainly affected by the incoming flow and sediment, as well as the surrounding terrain. However, after the formation of the sand spit, there
was an obvious relationship between the deposition and erosion distances and the epeirogenic area, as shown in figure 5. It can be seen from the figure that there was an approximately linear relationship between the deposition and erosion of the sand spit and the epeirogenic area. As detailed in figure 5, the deposition and extension at the front end of the sand spit had driven the deposition and extension of the coastline near the sand spit. As a result, the net epeirogenic area of the entire estuary area had become increased, and the deposition and extension speed had determined the size of the net epeirogenic area. Conversely, the erosion at the front end of the sand spit had caused the retreat of the coastline on both sides, and the erosion speed had affected the reduction of the land area.

3.2. Relationship between the incoming sediment and the epeirogenic area

The factors affecting the epeirogenic area in the Yellow River Estuary included the incoming flow and sediment, ocean dynamics, and the flow path. For the annual average situation of a certain flow path, the ocean dynamics were basically equivalent. Therefore, it was concluded that the decisive factors which had most affected the epeirogenic area were the flow and sediment. Among these, the incoming sediment was found to be the main influencing factor. Figure 6 shows the relationship between the incoming sediment from the Lijin Hydrological Station and the epeirogenic area in the estuary. It can be seen from the figure that when the incoming sediment was approximately 300 million tons, the epeirogenic area in the mouth region had basically reached a dynamic balanced state. Also, when the incoming sediment had reached approximately 900 million tons, the epeirogenic area in the mouth region had reached the maximum. Furthermore, when the incoming sediment was more than 900 million tons, the epeirogenic area had begun to decrease. The reason for these results may have been that the deposition of the tail channel reach had been more serious due to the larger incoming sediment, and the incoming sediment which had reached the vicinity of the sand spit had actually been reduced resulting in a decrease of the epeirogenic area.

4. Dynamic factors in the evolution of the mouth reach area

4.1. Persistent dynamic factors

4.1.1. Incoming flow and sediment. In accordance with the characteristic values of the flow and sediment during different periods which were obtained from the Lijin Hydrologic Station, the flow and sediment changes in the estuary area could be divided into three periods beginning in 1950. When compared with the first period, the annual incoming flow of the second and third periods was found to have decreased by 34% and 71%, respectively. Also, the annual incoming sediment had decreased by 42% and 73%, respectively, while the coefficients of the incoming sediment had increased by 11% and 163%, respectively. Therefore, it was determined that the flow and sediment variations had led to
the shrinkage aggravation in the estuary area. It was determined that after the diversion was completed in 1996, the incoming sediment in the estuary area was basically approximately 300 million tons, and the sand spit had become dominated by erosion and retreat. Also, the mouth bar area had not been fully developed at that time [7,8].

4.1.2. Ocean dynamics. The Yellow River Estuary has the characteristics of a microtidal estuary. The majority of the sea areas outside the flow path are characterized by irregular semi-diurnal tides. The average tidal range is known to be between 0.73 m and 1.77 m. The tidal range of the M2 amphidromic point located outside the No. 5 pile was found to be the smallest in the study area, and the flow velocity was the largest. It was observed that after the Yellow River Estuary was diverted to the Qingshuigou flow path in 1976, there had been two high-velocity areas near the Yellow River Estuary. These were the Shenxiangoukou and Qingshuigou flow paths. It was found that the maximum flow velocity change outside the Qingshuigou flow path was the most significant. The maximum measured flow velocity was 2.2 m/s. The influences of this high-velocity flow area on the evolution of the sand spit in the current flow path area were very significant. The residual flow velocity in the Yellow River Estuary was generally between 0.1 m/s and 0.3 m/s, and the wave height was generally between 1 m and 1.5 m. It was determined that after the waves had entered the shallow sea areas and breaks, the flow velocity was large. This is believed to have been the main influencing factor for the sediment transport along the coastal regions in the mouth area.

4.2. Accidental dynamic factors

4.2.1. Channel oscillations. In 1996, the Qingshuigou flow path was artificially diverted near the Qing-8-section, and the entrance to the sea was changed from the southeast to the northeast. At the time, the original old southeast flow path was in an erosion state due to the sand spit cut off. At the beginning of the new northeast flow path, the sand spit had become quickly extended, and was basically in a state of deposition and erosion dynamic equilibrium due to the continuous decreases in the incoming flow and sediment. It was observed from the distribution of the sediment deposition in the sea area that the advancing distances of the shallow water isobaths were greater than those of the deep water, and the different isobaths advancing shapes had all become flattened from bending. The thicknesses of the sediment deposition had ranged from 2 to 5 m, and the ranges of the sediment diffusion deposition in the shallow water areas were smaller than those of the deep water. The deposition volumes on the right side in the mouth area were observed to be larger than those on the left side and had presented an asymmetric shape.

4.2.2. Water-sediment regulations. Following the construction of the Xiaolangdi Reservoir, the ability to artificially regulate the flood peaks had become significantly enhanced [9,10]. The results of the water-sediment regulations in recent years have indicated that the sediment washed by the river during the water-sediment regulation processes will be carried to the mouth area, which will subsequently lead to the rapid development of the mouth bar. The analysis results of the measured data showed that for the period ranging from 2001 to 2002, two water-sediment regulations had deposited 33 million m$^3$ in the mouth area, and the area’s deposition thickness above 1 m was 11.1 km$^2$. By comparing the remote sensing images on May 8th and August 12th of 2002, it was found that during the water-sediment regulation in 2002, the epeirogenic area near the sand spit had reached 16 km$^2$, and the sand spit had been extended by approximately 4.1 km. The extension of the sand spit area was determined to be greater than the total cumulative extension of the six years after the branch of Qing-8-section was established.

4.2.3. Storm surges. Storm surges are destructive and powerful dynamic action within estuary areas. It has been determined according to preliminary statistics presented by Hu CH and Wang T that there have been six major storm surges in the Yellow River area in the past 150 years [2,11]. However,
smaller storm surges are known to occur all year round, particularly during the autumn-winter and winter-spring alternations. The increased water levels formed by storm surges have very strong erosion abilities. For example, in May of 1949, a storm surge had increased the water levels in the study area by more than 1 m for two consecutive days and had eroded approximately 7 m of the high-tidal line.

5. Conclusions
It has been found that the longitudinal extension speed of the mouth bar in the Yellow River Estuary is closely related to the incoming flow and sediment. For example, when the incoming flow and sediment levels are high, the longitudinal deposition and extension speed of the mouth bar tend to be fast. It was determined that there is an approximately linear relationship between the deposition and erosion distances and the epeirogenic area of the estuary. Furthermore, when the incoming sediment levels are lower than 300 million tons, the sand spit area in the mouth reach tends to present a state of erosion and retreat.

In regard to the types of gullies and branch channels, it was found that prior to 1996, flood gullies or tidal gullies were in the majority, and only six branch channels were connected the river and the sea. Among those, three branch channels were located on the each of the north and south sides. Then, after 1996, it was observed that the tidal gullies were in the majority, and the flood gullies had basically disappeared. The river channel was dominated by a single-strand main channel, and there were only 2 to 3 branch channels near the mouth area. In terms of the stability of the gullies and branch channels, it was confirmed that the gullies and branch channels in the east and north directions were relatively stable.

The evolution dynamic mechanism of the Yellow River Estuary was divided into two categories in this study as follows: persistent influencing factors and accidental influencing factors. The former mainly included the incoming flow, sediment, ocean dynamics, and so on, while the latter mainly included factors such as storm surges, channel oscillations, and water-sediment regulations. It was observed that although the time was short, the strengths of the influencing factors were large. In the current study, the evolution dynamic mechanism was determined to have had major influences on the evolution of the mouth reach area.

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