Evolution Trend of the Changjiang (Yangtze) Estuary with reduced incoming sediment

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Abstract. The reduction of fluvial sediment input has brought new features to the evolution of the Changjiang (Yangtze) Estuary. The response of river channels and shoals in the Changjiang Estuary are still unclear. A two-dimensional model of water and sediment transport in the Changjiang Estuary is established by using MIKE21. The sediment gradation and the flocculation of the fine sediment have been considered in the model. After calibration, the future evolution trend of the Changjiang Estuary was simulated based on the measured terrain in November 2016. The inflow of water and sediment at Jiangyin from 2008 to 2017 were taken as the upstream inlet conditions. The simulation results show that the pattern of river channel and shoals in the Changjiang Estuary will basically remain, and the main trend of bed evolution is erosion in deep channel and siltation of shoals.

1. Introduction
After the completion of the Three Gorges Reservoir, the flow process of water and sediment has changed greatly compared with the natural status, especially the severe reduction of sediment discharge[1]. In the context of a large amount of incoming sediment reduction in the upper reaches, the evolution of the Changjiang Estuary has also presented new characteristics[2, 3]. Based on the analysis of bathymetric data between 1880 and 2013 and related hydrological data, Mei[4] found that the deposition along the lower reach of the North Channel since 2003 can be explained by the landward sediment transport because of flood-tide force strengthen under the joint action of TGD induced seasonal flood discharge decrease and land reclamation induced lower reach narrowing. Luan[5] analyzed bathymetric data from the Changjiang Estuary between 1958 and 2010, conclude that both sediment discharge and river flood events played important roles in the decadal morphological evolution of the Changjiang Estuary. Zhao[6] analyzed morphological evolution in the Changjiang Estuary between 1958 and 2016, infer that the pan-South Branch is more fluvial controlled therefore its morphology responds to riverine sediment load reduction is fast while the mouth bar zone is more controlled by both river and tides that its morphological response lags to riverine sediment supply changes at a time scale > 10 years. The evolution of the Changjiang Estuary will have a certain impact on the flood control, navigation channel and utilization of the islands and shoals. Considering that the reduction of incoming sediment will continue for a long time in the future, it is necessary to predict and analyze the future evolution trend and its impact.
2. Model setup

This study was completed using MIKE21_FM and the mud module MT. The model is a planar two-dimensional model using unstructured grid. In order to adapt to the dramatic changes in the plane scale of the simulation area, different grid scales were adopted in different areas. Upstream the mouth of the Changjiang river the grid size is about 200 m, which increases to about 600 m at the mouth area. And the size of the grid outside the mouth is gradually enlarged up to about 10 km. The total number of grid cells is 71,778.

The distribution of the roughness coefficient in the calculation area is as follows: in Jiangyin–Xuliujing, the roughness coefficient gradually decreasing from 0.021 to 0.015 m$^{1/3}$s$^{-1}$; in the North Branch of the Changjiang Estuary, it is 0.010–0.011 m$^{1/3}$s$^{-1}$; in the South Branch and other river channels downstream the roughness coefficient is 0.012–0.014 m$^{1/3}$s$^{-1}$; in the offshore area outside the mouth, it is 0.010–0.011 m$^{1/3}$s$^{-1}$; in the deep sea area the roughness coefficient is 0.009–0.010 m$^{1/3}$s$^{-1}$.

At the open sea boundary of the model, the tidal level, which was extracted by the MIKE global tide model, was used. Before using in modeling, the phase and median value of the extracted tidal level should be adjusted to local time zone and height datum. The sediment concentration at the open sea boundary is set to zero. Flow of water and sediment concentration were provided at Jiangyin as river inflow boundary.

According to the measured suspended sediment and bed load grading in the Changjiang Estuary in August 2017, the median diameters of suspended sediment/bed load in the Changjiang Estuary during the spring and neap tidal periods were 0.013/0.11 mm and 0.008/0.13 mm, respectively. Therefore, the simulated sediment contains two types. The first type represents the viscous fine-grained sediment with the size among 0–0.031 mm, and the representative particle size is set to 0.008 mm. For this sediment, the flocculation effect is considered. The second type represents non-viscous fine-grained sediment, the size range is 0.031–1.0 mm. For this sediment, flocculation is disregarded, and the representative particle size is set to 0.11 mm. The settling velocity of the viscous sediment gradually increases from 0.1 mm/s at Jiangyin to 2.0 mm/s outside the mouth of the Changjiang river. The inviscid sediment has a settling velocity of 10.2 mm/s.

The thickness of the river bed is set to 15 m to fully meet the needs of possible erosion. The weight of the two sediments in the bed is given according to the measured data, and the proportion of viscous and non-viscous components accounts for 10% and 90%, respectively. The critical shear stress and erosion coefficient of the bed material are the parameters to be determined. According to experience and calibration results, the critical shear stress range is about 0.17–0.27 N/m$^2$, and the erosion coefficient range is about 1.5×10$^{-4}$–2.8×10$^{-4}$ kg/(m$^2$s). The recommended roughness height of the bed surface is 0.001 m.

3. Model calibrations

3.1 Tidal level

The Changjiang River Estuary Bureau of Hydrology and Water Resources Survey conducted a hydrological test of a complete spring and neap tidal process during the flood season in 2017 from 23 to 31 in August. During the test, 5 temporary tide stations were set up, including Ren Port, Wugan River, Fushan Gate, HSBC Terminal, and Dangxikou. Measured data at these stations were collected as well as the other 9 national or local basic tidal stations which are Jiangyin, Tiansheng Port, Yingchuan Port, Xuliujing, Chongtou, Baimao River, Xinjian River, Yanglin, Liuxiao. Therefore, data collected from a total of 14 tide stations were used.

Figure 1 illustrate the comparison of the simulated and measured tide level of the stations. It can be seen from the figure that the phase and amplitude of the calculated tide level fit well with the measured data.
3.2 Erosion and sedimentation

The terrain changes during November 2011 to October 2016 were simulated. The water flow and sediment concentration at the upstream boundary of the model is provided by a one-dimensional water flow and sediment transport model which covers from Datong to Xuliujing. According to observed data, the river bed evolution from November 2011 to October 2016 is shown in figure 2. It can be seen from the figure that: (1) The trend of erosion in deep trough and siltation on shoals in the Changjiang
Estuary is very significant; (2) The scouring and silting in the South Branch of the Changjiang Estuary is significantly affected by the fishbone works at the Baimaoshao shoal, where scouring can be found at both sides of the shoal; (3) In the upper section of the North Branch, erosion occurred in the deep trough while siltation on the side shoals; (4) In the lower section of the North Branch, siltation is dominant.

Figure 3 shows the simulated distribution of erosion and siltation of the Changjiang Estuary from November 2011 to October 2016. Comparing with figure 2, it can be seen that the simulated distribution is in good agreement with the observed data. The submerged breakwater at Baimaosha shoal and Xinliuhesha shoal, and the Deepwater Channel Regulation Project in the North Passage have a significant effect on bed evolution.

Table 2 shows the amount of erosion and siltation in each district. It can be seen from the table that the simulated amounts of erosion and siltation are basically consistent with the observed data.

Table 1. Coordinates of each tide station (central meridian of 120°E, Beijing 54 coordinate system).

| Tidal Station  | Coordinate | Tidal Station  | Coordinate |
|----------------|------------|----------------|------------|
| Jianyin        | 3535147    | 525598         | Xuliujing   | 3515726    | 590959 |
| Tiansheng Port | 3545806    | 570598         | Baimao River| 3512323    | 600906 |
| Rengang        | 3542925    | 577166         | Chongtou    | 3519276    | 609622 |
| Wugan River    | 3537609    | 572586         | Xinjian River| 3513302   | 614364 |
| Yingchuan Port | 3532961    | 585457         | Dangxikou   | 3506557    | 609564 |
| HSBC Terminal  | 3523269    | 588982         | Yanglin     | 3497350    | 619740 |
| Fushan Gate    | 3521916    | 580140         | Liuxiao     | 3488081    | 662072 |

Table 2. Statistics of deposition and erosion in each district.

| District                      | Jianyin ~ Xuliujing | South Branch | South Channel | North Channel | North Branch |
|-------------------------------|---------------------|--------------|---------------|---------------|-------------|
| Area (km²)                    | 558.36              | 641.47       | 200.91        | 206.12        | 384.02      |
| Average deposition thickness (m) | Observation -0.26 | -0.03        | -0.50         | -0.33         | 0.51        |
|                               | Simulation -0.32    | -0.15        | -0.38         | -0.44         | 0.41        |
| Volume of deposition (10⁴ m³) | Observation -14483 | -1924        | -9945         | -6761         | 19407       |
|                               | Simulation -17868   | -9622        | -7635         | -9069         | 15745       |
Figure 2. Measured scouring and silting distribution in the Changjiang River estuary from November 2011 to October 2016 (Unit: m)

Figure 3. Simulated scouring and silting distribution in the Changjiang River estuary from November 2011 to October 2016 (Unit: m)

4. Evolution prediction
The evolution of the Changjiang River estuary is predicted based on the terrain of November, 2016 and inflow of water and sediment at Jiangyin during 2008-2017. The incoming water flow and
sediment discharge is given by a one-dimensional water flow and sediment transport model which covers the range from Datong to Xuliujing. The parameters used in the prediction are the same as above.

4.1 Overall evolution
The average thickness of erosion-siltation in each district during every 5 years is shown in figure 4, and the cumulative average thickness is shown in figure 5. It can be seen from the figures that the South Branch is continuous scouring, and the scouring rate is not large. The cumulative average thickness of erosion in 20 years is about 0.70 m, that is, the annual average thickness is about 0.035 m. The South Channel experiences scouring in the first 5 years, and silting in the later 15 years, and the 20-year cumulative thickness of siltation is 0.73 m, that is, the average annual sedimentation thickness is 0.035 m. The North Passage keeps scouring in all 20 years and the accumulated scouring thickness reaches 2.34 m, that is, the average annual scouring thickness is 0.12 m. The South Channel experiences scouring in the first 5 years, and silting in the later 15 years, and the 20-year cumulative thickness of siltation is 0.73 m, that is, the average annual sedimentation thickness is 0.035 m. The North Passage keeps scouring in all 20 years and the accumulated scouring thickness reaches 2.34 m, that is, the average annual scouring thickness is 0.12 m. The upper section of the North Branch also continues scouring in the 20 years, and the accumulated scouring thickness reaches 2.28 m, that is, the average annual scouring thickness is 0.11 m. The lower section of the North Branch continues to be silting, and the accumulated siltation thickness in 20 years reaches 1.79 m, averaging 0.09 m per year.

According to the thickness of the scouring and silting, the cumulative amount of scouring and silting in each district was calculated. It can be seen from table 3 that scouring mainly takes place in the South Branch, the North Channel and the upper section of the North Branch. The large amount of scouring sediment from the South Branch is mainly due to the large area. While the large amounts of scouring sediment in the North Channel and the upper section of the North Branch are mainly due to the big erosion thickness.

![Figure 4. Averaged deposition/erosion thickness in every 5 years](image-url)
Figure 5. Cumulative deposition/erosion thickness in 20 years

Table 3. Statistics of predicted cumulative volume of deposition/erosion sediment in each district of Changjiang Estuary (Unit: 10^8 m³).

| Time  | South Branch | South Channel | North Channel | Upper section of North Branch | lower section of North Branch | Total    |
|-------|--------------|--------------|--------------|-------------------------------|-------------------------------|----------|
| 5 years | -1.39        | -0.28        | -0.78        | -0.14                         | 0.59                          | -2.01    |
| 10 years | -2.47        | 0.11         | -1.94        | -0.85                         | 1.91                          | -3.24    |
| 15 years | -3.14        | 0.77         | -3.35        | -1.64                         | 3.48                          | -3.88    |
| 20 years | -3.98        | 1.46         | -4.82        | -2.46                         | 4.94                          | -4.86    |

4.2 South Branch
The river regime of trough and shoals in the South Branch will remain unchanged. Baimaosha shoal is silted up, while its neighboring troughs are scoured. The head of the Upper Biandansha shoal is silted up and the tail is scoured, which makes it further separated from the Lower Biandansha Shoal. At the south side of the Lower Biandansha Shoal, the neighboring deep trough and has been scoured. The silt at the tail of the Lower Biandansha Shoal makes it longer. Deposition also occurs in the scattered area of the Xinliuhesha Shoal, which connects the shoal with the Changxing Island.

4.3 South and North Channel
The South Channel and North Channel basically maintain the initial status, that is, the main trough go through the North Channel. Most part of the North Channel is scoured, while the area adjacent to the southern margin of Chongming Island experienced remarkable silting. The area downstream of Qingcaosha Reservoir at the north of the Changxing Island silts, and the silting zone extending to the north of Hengsha shoal. The passage between the Changxing Island and the Hengsha shoal is also deposited. The South Channel is dominated by siltation while scouring occurs in the middle part of the trough. The south side of the tail of the XinLiuhehe Shoal is slightly scoured too. In the predicted results, area at the mouth of the Huangpu River's has significantly silted, which may be due to the fact that the model did not consider the inflow of the Huangpu River.

4.4 South and North Passage
In the South and North Passage, deposition is dominant. Of which, the deposition is quite evident on both sides of the submerged breakwater of the deep-water channel. Deposition also occurs on the front and north part of the Jiuduansha shoal. The central part and southeast area of the Jiuduansha shoal are slightly scoured.
Figure 6. Deposition/Erosion thickness of the South Branch in 20 years (Unit : m)

Figure 7. Deposition/Erosion thickness of the South and North Channels in 20 years (Unit : m)
Figure 8. Deposition/Erosion thickness of the South and North Passages in 20 years (Unit :m)

Figure 9. Deposition/Erosion thickness of the North Branch in 20 years (Unit :m)
4.5 North Branch
The North Branch is also characterized by a tendency of trough scouring and shoal silting. In the upper section of the branch, upstream of Xinlongsha side shoal, due to the narrow river channel, the shoals are narrow, and the deep trough swinging from bank to bank. At Chongtou, the deep trough lies at the right bank. It quickly transferred to the left bank, and keeps its location until after the turning. After the Lingdian port, the deep trough returns to the left bank, and back to right bank at the Xinlongsha shoal. At the Santiao port, the deep trough transfer to the left bank again. The downstream area of the Xinlongsha shoal on the north side of the Chongming Island is the planned narrowing area of the North Branch, which is dominated by siltation, but the siltation thickness is not big.

4.6 Outside the mouth
The surface of the Guyuansha shoal is scoured, but its southern area is remarkably silted, which causes the shoal to move southward.

The south side of the Spartina Alterniflora and the Bird Habitat Optimization Project in the Chongming Dongtan shoal is silted up, and its front edge forms a smooth line along the edge of the Chongming Island. On the east side of the edge, there is a deep trough scouring belt extending from the mouth of the North Channel. Part of the scouring belt is initially the northwestern part of the outer Tuanjiesha shoal. The result of the scouring is to further separate the outer Tuanjie shoal from Chongming Dongtan shoal. The east and south sides of the outer Tuanjiesha shoal are silted up, making it move towards southeast.
The front of the Hengsha shoal is silted up and the tail is scoured. On both north and south sides of it, due to the influence of the submerged breakwater, heavy siltation occurs. The result of its evolution makes the shape of Hengsha shoal consistent with the constraints of engineerings.

Outside the mouth of the Changjiang River, there are scouring belts connected to each other from the north to the south on the sea side of the shoals including Guyuansha shoal, outer Tuanjiesha shoal, Hengsha shoal, Jiuduansha shoal and Nanhui side shoal. The area with the largest scouring thickness is located at the mouth of the North Passage and the tail of the Nanhui side shoal, and the largest scouring thickness is about 9m.

5. Conclusions
A two-dimensional numerical model of water flow and sediment transport in the Changjiang River Estuary from Jiangyin to the open sea was established, and the evolution of erosion and siltation was predicted under the condition of reduced incoming sediment. The forecast indicates that there will be no major changes of the river regime of the Changjiang Estuary in the next 20 years; the scouring of the Changjiang Estuary will mainly occur in the deep troughs, and the scouring sediment is mainly come from the South Branch, the North Channel and the upper section of the North Branch. The scouring thickness is greater in the North Channel and the upper section of the North Branch. Outside the mouth of the Changjiang River, there are scouring belts connected to each other from the north to the south on the sea side of the shoals.

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