Numerical study on the morphological evolution of the Qingshuigou channel on the Yellow River Delta in response to changing water and sediment regimes

Sisi Chen1*, Zhiguo He1

1Institute of Port, Coastal and Offshore Engineering, Ocean College, Zhejiang University, Zhoushan 316000, China
* Corresponding author’s e-mail: sisichen18@zju.edu.cn

Abstract: The Qingshuigou channel is the longest channel in the modern Yellow River Delta since its diversion in 1976. To explore the morphological evolution of the Qingshuigou channel on the Yellow River Delta in response to changing water and sediment regimes, we applied the two-dimensional hydro-sediment-morphodynamic coupling model to simulate the characteristics of bed erosion and deposition in Qingshuigou channel and its estuary in different water and sediment regimes. The results demonstrate that regarding the seasonal difference of the year, the sediment deposition in the estuary during the flood season is larger than the non-flood season, and the former accounts for 88% of the annual estuary deposition. On a long-term scale, the erosion of the river channel becomes considerable and the sediment deposits rapidly in the estuary with high water discharge and sediment concentration.

1. Introduction
In recent years, the water and sediment discharge in the estuary have decreased annually, but they have become very high during the flood season and the Water-Sediment Regulation Scheme (WSRS), forming complex water and sediment regimes. The morphological evolution of the Qingshuigou channel in the Yellow River Delta (YRD) and its estuary with different incoming water and sediment are still unclear. Previous study has explored the influencing factors of the water-sediment changes and the relationship between the delta area and water-sediment conditions. In addition, some researchers have simulated and analyzed the sediment transport and topographic evolution of the Yellow River estuary. However, the interaction between channel and ocean dynamics and the nonlinear relationship among water, sediment and topography in morphological processes of the Qingshuigou channel receive less attention. Therefore, based on the two-dimensional hydro-sediment-morphodynamic coupling model, combined with satellite remote sensing images and measured topographic data, we established a large-scale numerical model of the YRD. The domain of this model starts from Lijin and end at 123° east longitude, including the Bohai Sea. We mainly focus on the erosion and deposition characteristics of the channel and estuary under the new water and sediment regimes. It is of great significance to scientifically formulate channel utilization plans and governance measures, and maintaining the ecological environment of the estuary.
2. Numerical model

2.1 Governing equation
The model was formulated based on depth-integrated shallow water models\(^6\). The governing equations are essentially comprised of flow continuity equation, momentum conservation equation, sediment transport equation and bed evolution equation. The finite volume method is used to solve the aforementioned equations. The governing equations can be written in matrix form as follows:

\[
\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = \frac{\partial \hat{F}}{\partial x} + \frac{\partial \hat{G}}{\partial y} + S
\]  

\[
U = \begin{bmatrix} h \\ hu \\ hv \\ hc \end{bmatrix}, \quad F = \begin{bmatrix} hu \\ hu^2 + gh^2 / 2 \\ hu \end{bmatrix}, \quad G = \begin{bmatrix} hv \\ hv \end{bmatrix}
\]  

\[
\hat{F} = \begin{bmatrix} 0 \\ T_{xx} \\ T_{yx} \\ \varepsilon_c (\partial c / \partial x) \end{bmatrix}, \quad \hat{G} = \begin{bmatrix} 0 \\ T_{yx} \\ T_{yy} \\ \varepsilon_c (\partial c / \partial y) \end{bmatrix}, \quad S = \begin{bmatrix} (E - D) / (1 - p_s) \\ gh(S_{bs} - S_{b}) + fhv \\ gh(S_{bs} - S_{b}) - fhv \\ E - D \end{bmatrix}
\]

\[
\varepsilon_c h = \frac{D - E}{1 - p_o}
\]

Here, \( x \) and \( y \) are the Cartesian coordinates; \( u \) and \( v \) are the depth-averaged velocities in the \( x \)- and \( y \)-directions, respectively; \( h \) is the flow depth; \( t \) is the time; \( U \) is the vector of conserved variables; \( F \) and \( G \) are the convective flux vectors in the \( x \)- and \( y \)-directions, respectively; \( \hat{F} \) and \( \hat{G} \) are the diffusive flux vectors in the \( x \)- and \( y \)-directions, respectively; \( S \) are the vectors containing source terms; \( g \) is the acceleration due to gravity; \( \varepsilon_c \) is the bed elevations; \( p_s \) is the bed sediment porosity; \( E \) and \( D \) are the sediment-entrainment and deposition fluxes, respectively; \( S_{bs} \) and \( S_{b} \) are the bed slopes; \( S_{bs} \) and \( S_{b} \) are the energy slopes; \( T_{xx} = 2\nu \partial u / \partial x \), \( T_{yx} = 2\nu \partial v / \partial y \) and \( T_{xy} = T_{yx} = \nu \left( \partial u / \partial y + \partial v / \partial x \right) \) are the depth-averaged Reynolds stress; \( \nu = \kappa u h / 6 \) is the turbulent viscosity coefficient; \( f \) is Coriolis coefficient; \( c \) is the depth-averaged volumetric sediment concentration.

2.2 Model setup
The model calculation range is 117.55°E~122.87°E, 37.14°N~41.05°N, starting from Lijin and encompassing the entire Bohai Sea (Figure 1). Using the world geodetic coordinate system WGS1984 UTM 50N, the open boundary spatial resolution is about 0.03°, and the shoreline spatial resolution is about 0.01°. The entire computing area is composed of 81458 nodes and 610504 cells. The model uses 46 field measured sections from April to July 2018 as the initial topography. The total simulation time is 1104 hours (July 1, 2018-August 15, 2018), and the calculation time step is 0.5 s. The upstream inlet boundary uses the water and sediment discharge at Lijin Station in 2018, and the global ocean tide model TPXO 7.2 is used to determine the tidal boundary conditions.

2.3 Model validation
The observation data of 6 tidal stations, 1 current station and 1 sediment station\(^7\) measured in 2018 were collected as verification data. The comparative results of tidal level, tidal current and sediment concentration are shown in Figure 2. The accuracy of model prediction is further evaluated by root mean square error (RMSE) and correlation coefficient (\( r \)), which are defined as equation (9) and (10). The
water discharge and bed erosion in the channel were also verified with the measured data during the flood season in 2018 (Figure 3). It can be seen that the calculated values are generally consistent with the measured values.

\[
RMSE = \sqrt{\frac{\sum(X_{cal} - X_{obs})^2}{N}}
\]

(9)

\[
r = \frac{\sum(X_{cal} - \bar{X}_{cal})(X_{obs} - \bar{X}_{obs})}{\left[\sum(X_{cal} - \bar{X}_{cal})^2(X_{obs} - \bar{X}_{obs})^2\right]^{1/2}}
\]

(10)

Here, \(X_{cal}\) is the calculated value, \(X_{obs}\) is the measured value and \(N\) is the total number of data.

Figure 1. The schematic diagram of model topography and gauge stations

Figure 2. The verification of (a) tidal level; (b) tidal current; (c) suspended sediment concentration
3. Results and discussion
The calculation cases are shown in Table 1, including the short-term scale and long-term scale. In the short-term scale, in order to further explore the morphological evolution of estuary during the flood season and non-flood season, the cases of flood season process from July to October in 2018 and the steady flow of low discharge and sediment concentration for 8 months are setup. In the long-term scale, the case of high water discharge and sediment concentration is setup to find the erosion and deposition characteristics of river channel and estuary.

| Case | Inlet boundary | Calculation time | Note |
|------|----------------|------------------|------|
| F1   | Flood season   | 4 months         | Water and sedimentation in the flood season |
| F2   | Non-flood season | 8 months | Q=600 m³/s, S=5 kg/m³ |
| I1   | High water discharge and sediment concentration | 10 years | Water and sedimentation in the flood season |

3.1 Flood and non-flood season
Figure 4 shows the distribution of erosion and deposition in the estuary during flood and non-flood periods. There is considerable sedimentation (within 10 m water depth) at the estuary during the flood season, and there is a trace of erosion at the mouth of the abandoned old Qingshuigou channel and the coast of the Laizhou Bay. During the non-flood season, the sedimentation at the estuary is very weak, only depositing (within 1-2m water depth) close to the estuary. However, the erosion at the mouth of the abandoned old Qingshuigou channel is greater than that in the flood season. The main reason is that the runoff and incoming sediment in the flood season are relatively large, which has a significant impact on the erosion and deposition of the river. The amount of sediment transported to the estuary in the flood season is much greater than that in the non-flood season. There is a certain amount of sediment replenishment to the abandoned old estuary in the flood season, making the erosion of the area less than non-flood season.

Specifically, the results show that the deposition area during the flood season is 1.62 km², while the deposition area during the non-flood season is 0.23 km²; the deposition volume during the flood season is 1.6464 million m³, and the deposition volume during the non-flood season is 227,200 m³. Regardless of the deposition area or the deposition volume, the bed-making effect during the flood season accounted for 88% of the total change in estuary sedimentation. This result is consistent to the 88% of the total amount of sediment entering the sea during the flood season as calculated in the 2018 the Yellow River sediment Bulletin[8], which shows the reliability of the model in the calculation of erosion and deposition in flood season.
3.2 Long-term scale simulation

Figure 5 shows the distribution of river erosion and deposition during high water discharge and sediment concentration. It is found that the river has considerable erosion on the main channel due to the great quantity of incoming sediment, and there is a trace of deposition along the way, mainly considering the large flow velocity caused by the water discharge. Figure 6 shows the changes of the estuary elevation. It is manifested that during high water discharge and sediment concentration, the river channel extends outwards rapidly, while a large amount of sediment is continuously transported to the estuary, and the elevation of the subaqueous delta is obviously raised.
Figure 6. Bed elevation at the estuary with high water discharge and sediment concentration

4. Conclusions
This study has simulated the characteristics of bed erosion and deposition in Qingshuigou channel and its estuary in different water and sediment regimes, which is of great significance to understand the evolution and development of Qingshuigou channel in the YRD and maintain the ecological stability of the estuary. Future research could continue to explore the evolution of the channel under extreme water and sediment conditions. The main conclusions about this research are as follows:

(1) Regarding the seasonal difference of the year, the sediment deposition in the estuary during the flood season is larger than that during the non-flood season, and the former accounts for 88% of the annual estuary deposition. However, because of a certain amount of sediment replenishment to the abandoned old estuary during the flood season, the erosion at the abandoned old Qingshuigou mouth is less than that in the non-flood season.

(2) On a long-term scale, the erosion of the channel becomes considerable and the sediment deposits rapidly in the estuary with high water discharge and sediment concentration. Besides, due to a large amount of sediment continuously transported to the estuary, the elevation of the subaqueous delta is obviously raised during high water discharge and sediment concentration.

Acknowledgments
This work was supported by "the National Key Research and Development Program: the Yellow River Estuary Evolution and Channel Stabilization Management Project (2017YFC0405502)".

References
[1] Wang H, Wu X, Bi N, et al. Impacts of the dam-orientated water-sediment regulation scheme on the lower reaches and delta of the Yellow River (Huanghe): A review[J]. Global and Planetary Change, 2017,157:93-113.
[2] Cui B, Li X. Coastline change of the Yellow River estuary and its response to the sediment and runoff (1976–2005)[J]. Geomorphology, 2011,127(1-2):32-40.
[3] Fan Y, Chen S, Zhao B, et al. Shoreline dynamics of the active Yellow River delta since the implementation of Water-Sediment Regulation Scheme: A remote-sensing and statistics-based approach[J]. Estuarine, Coastal and Shelf Science, 2018,200:406-419.
[4] Ji H, Pan S, Chen S. Impact of river discharge on hydrodynamics and sedimentary processes at Yellow River Delta[J]. Marine Geology, 2020,425:106210.
[5] Wu X, Bi N, Xu J, et al. Stepwise morphological evolution of the active Yellow River (Huanghe)
delta lobe (1976–2013): Dominant roles of riverine discharge and sediment grain size[J]. Geomorphology, 2017, 292: 115-127.

[6] Hu P, Lei Y, Han J, et al. Improved Local Time Step for 2D Shallow-Water Modeling Based on Unstructured Grids[J]. Journal of Hydraulic Engineering, 2019, 145(12): 06019017.1-06019017.9.

[7] Guo C, Wang C, Tang L, et al. Numerical analysis of the influence of sea level rise on sediment deposition in the Yellow River Estuary[C]. The 8th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science, Zhoushan, China, 2020.

[8] The Yellow River sediment Bulletin. Yellow River Conservancy Commission [EB/OL]. http://www.yrcc.gov.cn/zwzc/gzgb/gb/nsgb/.