The effects of saltwater intrusion on suspended sediment movement in estuary

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Abstract. A three-dimensional model of simplified riverine estuary was established with numerical simulation to investigate the distribution of estuarine salinity and suspended sediment under different flow rates. The spatial distribution of suspended sediment and deposition in the simulation were inspected. (1) There are two types of vertical distribution of suspended sediment, one increasing with water depth all the way and the other beginning with increasing and then followed by decreasing. (2) The head of salt wedge where the turbidity maxima is formed contributes to a large number of sediment deposition on bed; (3) With the increase of flow rates, saltwater intrusion is weakened, the corresponding turbidity maximum zone and the location of rapid sedimentation both moved toward the sea; (4) The estuarine circulation dominates the major processes of the turbidity and deposition at the salt front.

1. Introduction

Estuaries are at the junction of land and sea, and its environment is special [1]. The hydrodynamic condition of estuary is complex, so it is hard to study the current in estuaries and the movement of the sediment in the river. Gelfenbaum Gand Vale C et al. researched Columbia Estuary in the USA and Tagus Estuary in Europe respectively, analyzing changes of the distribution of suspended sediment concentration over time [2, 3], and Gelfenbaum G further studied the relationship between the distribution of suspended sediment concentration over time and the variation range of turbidity maxima. Lindasy Pet al. studied the temporal and spatial distribution and characteristics of suspended sediment concentration and grain size in long time series in the estuary of the Tagus river, discovering that flow velocity variation due to ebb and flood has an effect on suspended sediment concentration [4]. Based on a great deal of observed data of the Yangtze Estuary, Shen H T et al. researched the influence of flow rate and upstream sediment on the temporal and spatial distribution of suspended sediment, and analyzed the influence of mixing type and density circulation on suspended sediment transportation [5]. Through analyzing the observation data measured in 2010 and 2011 in the Changjiang estuary, Li Z H et al. ascertained the characteristics of intratidal and neap-spring variations of suspended sediment concentration and transportation, and discovered the flood-ebb variations remarkably affected the intratidal variation of suspended sediment concentration and sediment transport process [6, 7]. However, because of the complexity of the density stratified flow in the estuary and the vertical difference of the flow, the further studies of sediment movement and the settling law are still needed.

Based on the actual estuary, by taking advantages of the three-dimensional numerical simulation, a generalized idealized estuary model was established in this article. Through the test and calculation of
the model and analysis of the distribution characteristics of salinity field, sediment field and sediment deposition, the article studied the influence factors and dynamic contact between saltwater intrusion and suspended sediment movement in estuary.

2. Model set-up

2.1. Model settings

The model adopts the hydrodynamic module of Delft3D program, and refers to the geometric conditions of the actual channel. The tidal waterway uses trapezoidal prism shaped straight channel which bottom slope is 1:10000 and side slope is 1:8. The bottom width of the model is 1200m and water depth is 6m. After test comparison, the upstream boundary is determined to be 100km from the mouth of the estuary, which is basically unaffected by the tide. The calculated area and the plane grid are shown in Figure 1, and the water depth of the sea out of the mouth of the estuary increases linearly from the mouth to the depth of 30m.

The model adopts k-ε turbulent scheme, and the Manning coefficient is 0.020 outside the mouth of the estuary and 0.025 inside. The sediment parameters are shown in Table 1.

| Specific density (kg/m$^3$) | Critical bed shear stress for sedimentation (N/m$^2$) | Critical bed shear stress for erosion (N/m$^2$) | Dry bed density (kg/m$^3$) | Erosion parameter (kg/m$^2$/s) | Settling velocity (mm/s) | Initial sediment layer thickness at bed (m) |
|-----------------------------|------------------------------------------------------|----------------------------------|----------------------------|--------------------------------|-------------------------|-----------------------------------------|
| 2650                        | 1000                                                 | 0.5                              | 500                        | 0.0001                         | 0.25                    | 0.05                                    |

Figure 1. The calculated area and the plane grid.

2.2. Boundary and initial conditions

The upstream open boundary is given the flow conditions. Salinity and sediment concentration is set as 0 and 0.1kg/m$^3$ respectively. The downstream open boundaries of sea area are driven by a sinusoidal diurnal tide and tidal range is 1.0m. The tidal process is shown in Figure 2. The model started up in the only consideration of salinity and was preheated for 30 days, then restarted with sediment for 40
days. After the stability of the sediment calculations, one cycle from 0:00 9/12/2016 to 0:00 10/12/2016 was chosen to analyze.

![Tidal process at the boundary of open sea.](image)

**Figure 2.** Tidal process at the boundary of open sea.

### 3. Results and discussions

#### 3.1. The distribution of suspended sediment

As shown in Figure 3, in the range of the runoff rates chosen to test, the sediment concentration increased when the flow increased, but basically the suspended sediment concentration of the channel upstream is 0.1 kg/m$^3$. The suspended sediment concentration of the sea area outside the mouth of the estuary is almost 0. Around the mouth of the estuary appears a high concentration zone whose concentration is higher than that upstream and downstream reaches, namely turbidity maxima. As shown in Table 2, the concentration in the maximum turbidity zone is 2-6 times as much as that the upstream and downstream reaches. The sediment concentration in the core of turbidity maxima decreases with the flow rate increase.

The vertical distribution of suspended sediment concentration increases with the water depth on the upstream side of turbidity maximum zone and increases first and then decreases with water depth on the downstream side.

| Discharge(m$^3$/s) | 2000 | 2500 | 3000 |
|-------------------|------|------|------|
| The maximum concentration upstream(kg/m$^3$) | 0.112 | 0.104 | 0.104 |
| The maximum concentration of the maximum turbidity zone(kg/m$^3$) | 0.640 | 0.460 | 0.230 |
| The maximum concentration of the sea(kg/m$^3$) | 0.002 | 0.005 | 0.004 |

#### 3.2. Influence of saltwater intrusion on suspended sediment distribution

Because tide has an effect of enrichment on sediment [8] and there is a detention point near the head of saltwater wedge, the sediment accumulates around the detention point [9]. The density circulation caused by saltwater intrusion results in the formation of turbidity maximum zone. As shown in Figure 4, combined with the distribution of salinity, turbidity maxima is located at the position of the head of saltwater wedge. When changing the flow, the trend of their movements are similar to and their positions are corresponding.
Figure 3. Suspended sediment concentration under conditions of the flow rates of 2000 m$^3$/s (a,b,c,d), 2500 m$^3$/s (e,f,g,h) and 3000 m$^3$/s (i,j,k,l).
Figure 4. Profiles of salinity and suspended sediment at flow rates of 2000 m$^3$/s (a,d), 2500 m$^3$/s (b,e) and 3000 m$^3$/s (c,f) at the same time.

3.3. Settling characteristics
As shown in Figure 5, the upstream tidal channel was eroded and sediment layer thickness at bed decreased. Within the movement range of turbidity maximum zone, rapid deposition of sediment made the bed level raised and the thickness of sedimentary layer increases greatly. When changing the flow rate, the position where the bed uplifts stays in the intermediate of turbidity maximum zone and changes longitudinally with it.

4. Summary and conclusions
The numerical simulations with a three-dimensional model for a simplified estuary were conducted in this paper in order to investigate the distribution of suspended sediment in salt water and response to the saltwater intrusion. Based on the numerical experiments and analysis, the following conclusions are drawn. (1) Under the conditions of the suggested runoff flow, the turbidity maximum where the sediment concentration is 2-6 times as much as that in the upstream and downstream occur near the front zone of salt wedge. Consequently, there are two types of vertical distribution of suspended sediment concentration, increasing with water depth and increasing only in the upper layer but decreasing in the lower layer with water depth. (2) The location of turbidity maximum zone is closely related to the salt water movement, and largely depends on the position of the saltwater wedge head.
Within the range of turbidity maxima movement, a large number of sediment settle on the bed, leading to an evident rise of the bed level near the head of the saltwater wedge. Further research work should be given to internal dynamic processes of turbidity maximum as well as inherent relationship between movements of sediment and saline water in riverine estuaries.

![Figure 5. Sediment thickness at bed at the flow rates of 2000m$^3$/s(a), 2500m$^3$/s(b) and 3000m$^3$/s(c).](image)

**Acknowledgment**
The project is financially supported by National Natural Science Foundation of China (No. 11572130) and National Key Research and Development Program of China (No. 2016YFC0402601).

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