A numerical experiment on tidal river simplification in simulation of tide dominated estuaries

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Abstract. In numerical simulation of tide dominated estuaries, introduction of simplified tidal channels into the model for real rivers is one of the strategies to deal with the lack of topographic data. To understand the effects of simplification and their sensitivity to the simplifying parameters, a numerical experiment was conducted to test the parameters such as channel length \( L \), surface width \( B \), bed slope \( S \), bottom elevation \( V_0 \), bed roughness \( u \) and runoff \( Q \). The results indicated the values of those parameters which were liable to less tidal prism and greater flood resistance would result in larger simulation errors. For a better simplification the values of parameters for the channel geometry, resistance and upstream inflow needed to be consistent with the average of the natural river as much as possible. The simplification method made the computation stable, fast and saved the storage space and it was adoptable for different time periods and seasons.

1. The Introduction

Estuarine hydrodynamic processes are fundamental to such as aquatic environment, sediment transport and topographical evolution in estuaries. During simulation of them the boundary condition at river end is notably affective to stability and precision of computation [1,2]. In terms of characteristics of hydrodynamic equations and usual discrete procedures of solution, giving flow flux to the landward upstream for inflow while tidal stage to the seaward downstream boundary is commonly favorable to computation stability and convergence [3-5].

In most of tide dominated estuaries there are usually horizontally extensive regions open to sea with funnel shapes. The tidal rivers in the upstream would be quite long or even several times the estuary bay if they have mild slopes, e.g. Delaware Bay, Columbia River estuary and some of sub-estuaries of Pearl River [6-8]. When simulating such estuaries, if the upstream boundaries are situated beyond tidal current range or even tidal limit, the computational region and time consumption will greatly increase and entire topographical data of the long rivers are requested, which sometimes troubled the workers. If we turn to take the head of bay as open boundary, it is not often satisfactory to the computation for significant tidal influences. Therefore, it is a technical problem often met in practice and expecting solutions that how to handle the upstream tidal rivers and their open boundaries economically and conveniently, and in the meantime to ensure the dynamical conditions of the entrance to main body of the estuary.
For this purpose, people used to apply 2-D or 3-D models nested by 1-D models or tried to constitute model of larger and coarser grid system so as to supply boundary conditions for finer simulation of smaller local regions in the estuaries [9,10]. Although some researchers adopted simplified rivers, they didn’t discuss the specifications or rules for the simplifications [7]. Now the question is when we take the latter method, what aspects in the simplification are important to the modeling accuracy? This is our motivation to investigate by means of numerical experiment with the case of Huangmaohai estuary of Pearl River and its upstream Yamen waterway and Tan River.

The next part will represent simulation model and study method, then be followed by discussion of the test results and finally the conclusions.

2. Location, model and method

Shown as in figure 1, Huangmaohai estuary bay is located in the middle of the coast of Pearl River delta facing to China South Sea, connecting two of eight sub-inlets of Peal River estuary, Yamen and Hutiaomen.

![Figure 1](image1.png)

**Figure 1.** Geo-location of Huangmaohai estuary and the simulation area. The closed triangles in (c) indicate hydrological stations while the open tide stations. The red solid line circles the area with actual terrain in the computation.

The estuary area in our numerical experiment applied the actual topography in 2003 and was gridded as shown in figure 2. The simplified channels were straight and prismatic, substituting for the real upper tidal rivers. The farthest seaward boundaries reached the 30m isobaths where the tidal level conditions were given by the global ocean tide model, while the upstream boundaries at the simplified river ends were given flow rate series.

![Figure 2](image2.png)

**Figure 2.** Computational Grid. Upstream the broken signs, two simplified channels are added to the zone with actual terrain. Some lengths of the channels are omitted in the figure.

The model was operated by the 2-D hydrodynamic module of Delft3D software developed by Deltares and k-ε model was chosen for turbulence calculation. The values of bed roughness were also simplified to be some constants, i.e. 0.012 and 0.014 for estuary bay and open sea respectively but a tested value for the tidal rivers. The simulation covered 10 days dating from 7 to 16 in February, 2001, incorporating spring to neap tides. Owing to the dry season for that time, the upstream run-off flow was stable and thought to be approximately steady. The wind and wave were neglected in the computation due to fine weather during most of the time.
Numerical tests were carried out for the simplified channel length $L$, surface width $B$, bed slope $S$, bottom elevation $\theta_0$, bed roughness $n$ and run-off $Q_r$ one by one. Due to the higher bottom and the smaller cross-section area, for simplicity, the simplified parameters for Hutiaomen waterway were given the averaged values of the actual river all the time. Four major observation points were Guanchong, Xipaotai, Hushan and Hebao Island in figure 1 (c). The simulated hourly levels and flow rates at these points were compared with the on-site observation values.

The root mean square of level or flow rate error were calculated as follows

$$RMS = \left[ \frac{1}{k} \sum_{i=1}^{k} (L_i^p - L_i^m)^2 \right]^{1/2}$$

where $L_i^p$ and $L_i^m$ were hourly values in proto observation and model computation respectively, with the hour numbered by $i$ in total simulation hours $k$.

For sensitivity analysis, firstly, a reference experiment had been conducted as follows. The upstream boundary flow was given the average of the observation in simulation period, the length and slope of the channel were given the general values based on the real river. The width followed the breadth of the cross-section that connected the un-simplified waterway because the actual width varies mildly. Further, the Manning’s roughness was chosen by modulations till the minimum calculation errors at the observation points were reached. On the basis of this reference experiment, taking its simplifying parameters and the corresponding $RMS$ values as benchmarks, we conducted comparative tests. Then the percentage change of the tested parameter $\eta_1$ and that of the corresponding $RMS$ $\eta_2$ at Guanchong, the entrance to the main body of the estuary bay, were calculated, respectively.

$$\eta_1 = \frac{P_m - P_0}{P_0} \times 100\%$$

$$\eta_2 = \frac{RMS_m - RMS_0}{RMS_0} \times 100\%$$

where $P$ denoted the tested parameter such as $L$, $B$, or $\theta_0$ etc. and the subscripts $0$ and $m$ denoted the benchmark and the otherwise modeling respectively. Thus, through the variation of $\eta_2$ with $\eta_1$, the sensitivity of the computed estuarine dynamics to the variation of simplifying parameters could be assessed in some way.

3. Discussions

3.1. The results of reference experiment

The simplifying parameters of the reference experiment was configured as follows, $L=100$km, $B=1000$m, $S=0.0001$, $n=0.0135$ and $Q_r=300$m$^3$/s. The computed results are shown in figure 3. It was found to be the best in general among all the tests.

3.2. Sensitivity analysis

The relationship of $\eta_1$ for each parameter and the corresponding $\eta_2$ is demonstrated in figure 4. On overall, most of the parameters have much greater influences on tidal flow than on tidal level.

By comparing the results in figure 4, we found decreasing of $L$ had greater effects on both tidal level and flow than the other changes but increase of it brought very small effects. The influence of decrease of $B$ stood the second place to tidal level but increase of it had less effects.

The $RMS$ of tidal level was quite sensitive to increasing $S$ but not remarkable to decreasing of it. By contrast, the tidal flow was always sensitive to $S$ whether it is raised or not. Relative to the average water depth, when bed rising was less than 25%, the tidal level $RMS$ was commonly below 3%, otherwise, the error went up quickly. Yet bed lowering brought much mild effects on tide level $RMS$. But for the tidal flow rate, there was an obvious difference with that, the reduction of bottom elevation became the most sensitive parameter while the rising bed are not and slightly bed lifting even diminished the flow $RMS$. 

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Figure 4. Percentage variations of computational error at Guangchong to simplifying parameters. (a) For tidal level. (b) For flow rate.

As for the bed roughness, it seemed not influencing as imagined whether to the tidal level or to the flow rate. And, the result errors of all runoff tests were not outstanding compared to that of the other parameter tests, especially for the tidal flow. Moreover, both RMS varying linearly with the runoff changes was another feature of the parameter.

When we classified the parameters according to the effects on tidal prism or tide storage, except the runoff, we found that for tide level errors, all changes that enhanced the prism such as increase of $B$ or $L$ and decrease of $S$, $V_0$ or $n$ affected less. If these parameters were changed inversely, i.e. the prism was reduced, the computation errors showed high sensitive dependence. In addition, decrease of $Q_r$ resulted in negative $\eta_2$, which indicated less errors than in the reference experiment. The tidal level RMS reached the minimum when $Q_r$ was zero.
3.3. The best simplification

In order to comprehend the best combination of the simplified parameters, we investigated the information of Tan River through relevant documents. In the early 1980s, in the upstream near Xiangang Town a controlling sluice was constructed and then the tidal reach actually has an average bed slope of $0.7 \times 10^{-4}$. When the slope in reference experiment was calibrated to that, the flow $RMS$ in Guanchong showed decrease by 2.7%. In addition, for channel length, 50% increase of $L$ resulted in a little higher accuracy of computation. This implied the true tidal limit was in the upstream of the sluice project which was the real fact and accorded with the conclusion of other researchers' simulation [11].

![Figure 5](image)

**Figure 5.** The verification places S8–S13 in downstream of the estuary. The darker line indicates the shipping lanes in planning.

![Figure 6](image)

**Figure 6.** The current verification for S8 and S13 from daytime 20:00 on 1 to 2:00 on 3 in January and S10 and S11 from daytime 9:00 on 27 to 12:00 on 28 in June. True north direction is specified as zero degree. The current direction data in June was missing.
3.4. Flexibility of the simplification
After adopting the optimized length and slope in subsection 3.3, with the other parameters the same as the benchmark except for the runoff, we chose two springs in January of dry season and June of flood season in 2010 to simulate respectively, with the verification points shown in figure 5 and the current results in figure 6. The computed and the measured showed a good accordance in overall, which implied the simplification as well as the parameters can adapt to the different seasons.

4. Conclusions
We conducted numerical experiments by case of Huangmaohai estuary of Pearl River to investigate effectiveness of simplified tidal channels in upstream and significance of the simplifying parameters on hydrodynamics in top of estuary bay. The results show that in simulation of tide dominated estuary if the upstream boundary cannot set to the actual tidal limit due to lack of topographical data or saving computational resources and time, we can choose to simplify the tidal rivers to a straight prismatic channels. During the simplification, the fundamental features of actual tidal prism geometry and resistance characteristics should be maintained. Among the parameters those may diminish the tidal storage and add the resistance to flood tide would result in larger hydraulic calculation errors and they have to be put more cautions and handled more carefully in the simplification.

The simplification method makes the computation stable and fast as well as saving the storage space to some extent. It is adoptable for different time periods and seasons.

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