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Numerical Study on the Transport Timescale in a River-influenced Macro-tidal Estuary

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ABSTRACT

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A transport module was developed and coupled with TELEMAC flow model to simulate the spatial and temporal distributive characteristics of the transport timescale based on the mean age concept defined by Delhez. The influences of river discharge, tide and large-scale flat reclamation in Taizhou Bay on the transport timescale were analyzed. Model results show that the transport timescale in the river channel is dominated by fluvial discharge over tide. It took approximately 60, 40 and 35 days for the tracer to be transported from the river boundary to the mouth of the Jiaojiang Estuary during the low, mean and high flow conditions, respectively. Outside the entrance of the estuary, tide dominates and the influence of riverine discharge is minor. Large-scale reclamation considerably affects the age distribution outside the estuary and around the project area, while it has little influence on the mass transport in the upstream part of the estuary. After the reclamation, the difference in mean age between the main channel and the tidal flat increases and the tongue-shaped spatial structure of mean age is more evident.

ADDITIONAL INDEX WORDS: *Jiaojiang Estuary, transport time, TELEMAC, numerical model, tidal flat reclamation.*

INTRODUCTION

In aquatic systems, most of the living biomass and nutrients, contaminants, and suspended particles are carried in a fluid medium. As is well known, major processes controlling the distribution of planktonic biomass and contaminant in semi-enclosed bays are linked to transport timescale (*e.g.,* Brye *et al.,* 2012; Monsen *et al.,* 2002). Since the 1970s, many timescales have been introduced to quantify the exchange and transport processes, including flushing time (Bolin and Rodhe, 1973), age (Zimmerman, 1976), residence time (Takeoka, 1984), turnover time (Monsen *et al.,* 2002), exposure time (Delhez, 2013) and *etc.* Among these timescales, age of a seawater particle (i.e., the time spent for a certain particle entering a predefined region until leaving the region) is widely used for hydro-environmental assessment. Schematically, age was used for three main purposes: (1) estimating the ventilation rate of lakes, estuaries, and ocean basins (*e.g.,* England, 1995), (2) inferring the horizontal circulation of shelf seas (*e.g.,* Delhez and Deleersnijder, 2002) and (3) quantifying pollutant transport in aquatic system (*e.g.,* Deleersnijder *et al.,* 2001). To be more specific, age in this study is defined to be the time that elapses before a conservative substance is discharged into the headwater of the estuary. Therefore, age is zero at the headwater of the estuary and age at any other location is representative of the timescale for a conservative substance to be transported from its source to this location. Delhez *et al.* (1999) introduced an Eulerian theory of age, in which advection and diffusion, production and destruction phenomena were properly accounted for. This theory provides a general method for using numerical models to compute spatially varying age distributions in a real estuarine environment, which has been calibrated and used for many studies in channels, reservoirs, gulfs and estuaries (*e.g.,* Delhez *et al.,* 2002; Shen *et al.,* 2011; Zhang *et al.,*2010).

River-influenced macro-tidal estuaries are usually characterized by high flood-dry runoff ratio, large tidal range and strong tidal action (Tang, 2003). Different from partially mixed or slowly mixed estuaries, the mass transport characteristics of the river-influenced macro-tidal estuaries are remarkably affected by both the river runoff and tides (Brye *et al.,* 2012; Monsen *et al.,* 2002). Therefore, it is essential to understand the hydrodynamic processes that transport water and other associated constituents in this kind of estuaries. The Jiaojiang Estuary is a typical river-influenced macro-tidal estuary located in the central Zhejiang Province, Eastern China (Figure 1). The annual averaged freshwater discharge in the estuary is around 163 m^3/s (with marked yearly variations); the annual runoff reaches 289 m^3/s in the rainy year but decreases to 72 m^3/s or less in the dry year (Tang, 2003). The tidal signal is semi-diurnal and slightly asymmetrical. Its average tidal range reaches about 4 m and the maximum tidal range can exceed 6 m.

Macro-tidal estuaries are also often characterized by the presence of extensive tidal flats. The Jiaojiang Estuary is funnel-

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shaped and the offshore area of Jiaojiang Estuary is called Taizhou Bay, where large areas of tidal flats are present. In recent decades, a lot of reclamation projects of tidal flats around the estuary have been conducted. By interpreting the remote sensing images of coastlines in different years we found that approximately 106 km^2 of coastal wetland had been reclaimed in Taizhou Bay between 1984 and 2013. Tidal flat reclamation not only affects hydrodynamic characteristics (Zhang *et al.,* 2015), but also alters mass transport behavior in the estuary. The purpose of this study is to understand the response of the transport timescale to different dynamic conditions and the impact of the large-scale reclamation of tidal flats on the transport processes in a river-influenced macro-tidal estuary.

METHODS

A mass transport module based on Delhez's theory was developed and coupled with the TELEMAC-2D hydrodynamic model which solves the shallow-water equations based on the classical Boussinesq and hydrostatic pressure assumptions (EDF-DRD, 2013). The equations are solved by a finite element method using a triangle mesh. The coupled model was applied to the Jiaojiang Estuary and its adjacent coastal sea in this study.

The grid domain comprises the Jiaojiang River and Taizhou Bay offshore areas and the open boundary was extended sufficiently far seaward to minimize the lack of precision in the tidal forcing at the open boundary, and the river boundary is extended 100 km upstream to Sanjiangkou Station (Figure1). This station locates at the origin of Jiaojiang River and serves as the controlling station for the measurements of the Jiaojiang freshwater discharging into the sea. Triangular Cartesian grids were used in the model. The entire grid consists of 29022 triangular elements of variable sizes with 1 km resolution near the seaward open boundary and 50 m along the river channel. For the horizontal turbulent diffusion, a Laplacian-type horizontal viscosity coefficient is computed from Smagorinsky's formulation (Smagorinsky, 1963), depending on local mesh dimensions and velocity gradients.

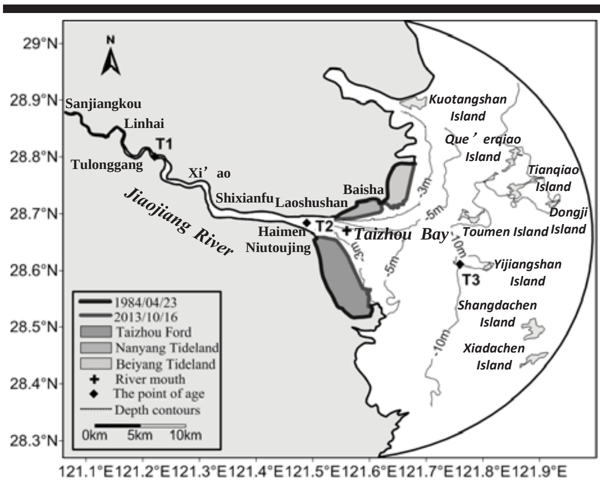

Figure 1. Map of Jiaojiang River Estuary area and model domain.

Tidal level forced the model at the open boundary, which was obtained based on the model results of the Taizhou Bay simulation of Zhang *et al.* (2015). The model has the same characteristics as the local model and has been validated against observed water surface elevations and tidal currents at various stations along the estuary (Zhang *et al.,* 2015). The output of the Taizhou Bay model is interpolated in time and space and prescribed to the local model using a radiative open boundary condition. At the upstream boundary, where tidal effects are negligible, the long-term mean freshwater discharge of 163 m^3/s, the annual freshwater discharge of 289 m^3/s in the rainy year, and the annual freshwater discharge of 72 m^3/s in the dry year were used to represent the respective mean, high and low flow conditions of the estuary.

Several methods have been introduced for computing the tracer age in the literatures (*e.g.,* Bolin and Rodhe, 1973; Takeoka, 1984; Zimmerman, 1976). Delhez *et al.* (1999) introduced a general age theory. Based on the general age theory, the age of a substance can be computed by solving two advection-diffusion equations. The first equation governs the concentration C of the substance while the second governs the age concentration α of the substance.

$$\frac{\partial HC}{\partial t} + \nabla \cdot \left(H\vec{u}C \right) = \nabla \cdot \left(HK \cdot \nabla C \right) \qquad (1)$$

$$\frac{\partial H\alpha}{\partial t} + \nabla \cdot \left(H\vec{u}\alpha \right) = \nabla \cdot \left(HK \cdot \nabla \alpha \right) + HC \qquad (2)$$

Where H is the water depth, $\vec{u}$ is the depth-averaged horizontal velocity, K is the diffusion coefficient. The age a of the substance is then computed as follow:

$$a = \frac{\alpha}{C} \qquad (3)$$

A detailed description of their theory is referred to Delhez *et al.* (1999) and Deleersnijder *et al.* (2001).

Two passive tracers without decay were simulated to represent transport of a dissolved substance and the age respectively. The concentration of the dissolved substance was set to 1 (arbitrary units) and the age concentration was set to zero at the head of the river. When the tracer flux outflows from the open boundary, the tracer is calculated from the advection equation. The incoming tracer concentration from the open boundary was set to zero. That implies that no tracer sources come from the downstream of the estuary. The model was initially run for 25 days for each flow condition to obtain a dynamic equilibrium condition. The flow fields under this equilibrium condition were used as the initial condition for the model experiments so that the model experiments could be "hot" started. The model experiments were conducted for 130 days. The dynamic equilibrium condition was obtained at about 80 days, 100 days and 120 days near the York River mouth for the high flow, mean flow and low flow conditions, respectively. We are more interested in the age distribution under this equilibrium condition. Therefore, the averaged mean age is calculated after the dynamic equilibrium is attained.

RESULTS

The time series of the age and the water level in the last two days at station T1, T2 and T3 (Figure 1) under the mean flow condition are represented to investigate the age distribution characteristics at a specific location. As shown in Figure 2, in constant runoff condition, a dynamic equilibrium condition was attained and the age varies with the change of the tidal level due to the influence of the tide.

The mean age distribution under the mean flow condition after tidal flat reclamation is shown in Figure 3. The numbers shown on the contour lines are the mean ages of the substance in days at that location. The result shows that a substantial time is required for a substance to travel downstream in the estuary. The substance released under the mean flow condition will take about 10 days and 35 days respectively to be transported to the middle of the Jiaojiang River near Xi'ao and the mouth of Jiaojiang River. In general, the age contours gradually turns to the right outside of the estuary, which can attribute to the influence of bathymetry, Coriolis force, and tidal asymmetries.

One notable feature of the spatial structure of mean age in the Jiaojiang Estuary is that it showed a tongue-shaped pattern along the main channel connecting the open sea, with low tracer age in the middle of the channel and relatively high tracer age in the shallow areas adjacent to the shoreline (Figure 3). The result suggests that more substances are transported out of the estuary from the deep channel meandering through the estuary. This tongue-shaped pattern resembled the residual current distribution with large downstream residual currents located in the middle of the channel and low upstream residual currents located in the shallow areas adjacent to the deep channel (Tang, 2003).

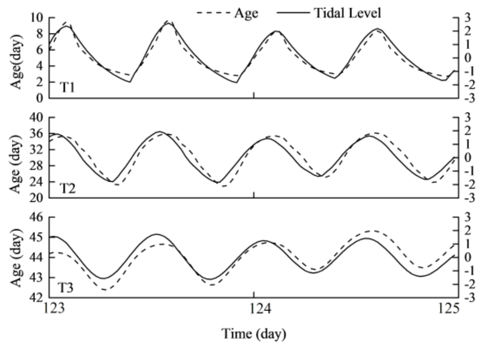

Figure 2. Age and tidal level hydrographs.

DISCUSSION

The age distribution is a function of both tide and freshwater discharge. To examine the influence of river discharge and spring-neap tide on age distribution, we compared the model simulation results of mean age during spring tide and neap tide under low, mean and high flow condition. Besides, to investigate the impact of large scale tidal flat reclamation on the age distribution, a model simulation with tidal flats is conducted (in 1984).

The influence of river discharge and spring-neap tide on the transport timescale

It can be seen that under the some flow condition, the mean ages in the river channel during spring tide and neap tide are almost the same (Figure 4). It means that spring-neap tide has almost no influence on the age distribution in the river channel. However, under a low flow condition, the substance need almost 35 days to be transported out of the estuary after it enters the headwater of the estuary. Compared to the model result under a high flow condition, the transport time under a low flow condition is almost 25 days slower. The transport time under a high flow condition is also faster than that under mean flow (close to 40 days). This suggests that freshwater inflow is one of the dominant factors in controlling transport processes in the Jiaojiang River channel.

Although the model reaches dynamic equilibrium, the model results in the outside of the estuary vary from neap tide to spring tide. The age difference can also be considered as due to the difference of the tracer releasing time (*i.e.,* the tracer is released during spring or neap tides). In the outside of the estuary, for example, the age around the Yijiangshan Island minus the age at the mouth during spring tide under high flow condition is the same with that under low flow condition, both are about 14 days. The model results indicate that tide dominates and the influence of riverine discharge is minor outside the entrance of the estuary.

Remarkably, the tongue-shaped spatial structure of mean age is more evident during spring tide under a low flow condition. This pattern agrees well with the residual current features of Taizhou Bay (Tang, 2003).

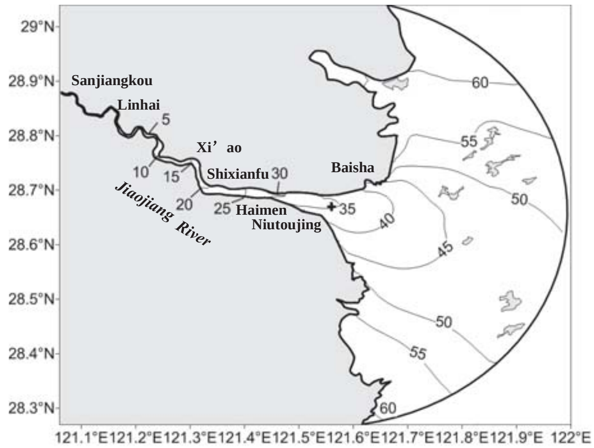

Figure 3. Spatial distribution of averaged age after reclamation.

The influence of tidal flat reclamation on the transport timescale

The model results show that the age distribution of the tracer has been changed after the large-scale of tidal flat reclamation. Compared with the model result without tidal flats (Figure 3), the average age of substance near the river mouth is about 5 days by excluding the tidal flats than by including it. Note that the difference with and without tidal flats only occurs in the downstream portion of the river and around the tidal flats where the reclamation projects persist. There is almost no difference in the upper portion of the Shixianfu. A notable increase of the tracer age occurs in the mouth of the estuary and around the tidal flats after the large scale tidal flat reclamation. The largest increment of the tracer age can reach approximately 5 days.

Under the mean flow condition, the tongue-shaped spatial structure of mean age is more evident, suggesting more substance is discharged out of the estuary through the middle of the channel after the large scale tidal flat reclamation. The cause of the change is largely due to the shrink of the shoreline after large-scale reclamation, which leads to the changes of flow velocity and direction around the project. After the reclamation, the flow velocity of flood tide is hindered by the funnel-shaped estuary, which leads to the reduction of the flow velocity. At the same time, the decrease of the tidal prism due to the large scale tidal flat reclamation result in the reduction of ebb velocity.

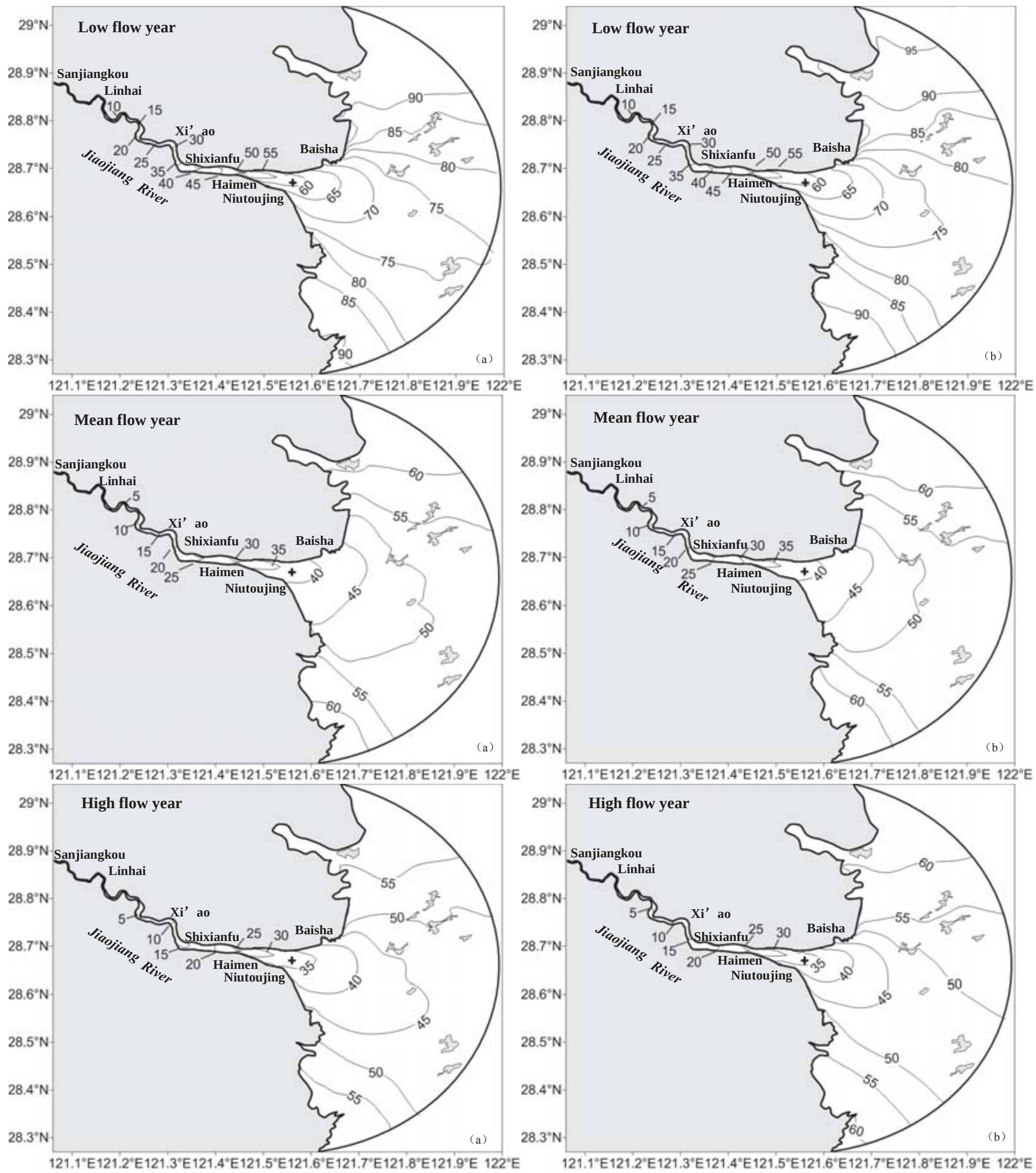

Figure 4. Spatial distribution of averaged age (in days) under different river discharge conditions (panel a shows age during spring tide, panel b shows age during neap tide).

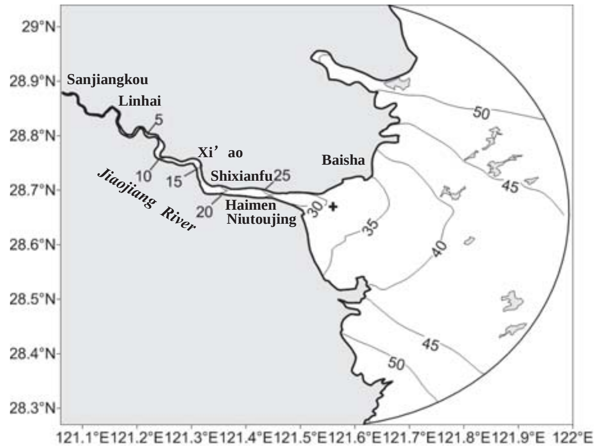

Figure 5. Spatial distribution of averaged age after reclamation.

On the other hand, the wetland turns into land, which leads to that more freshwater is discharged out of the estuary through the middle of the channel, makes the age difference between middle channel and shallow areas increase. Whereas the project has almost no influence on the age distribution in the upper portion of the Shixianfu since the project is far away from it.

CONCLUSIONS

The Jiaojiang Estuary, a typical river-influenced macro-tidal estuary, is used as a representative estuary to gain in-depth insight into the rate of mass transport of pollutant from upstream to the downstream estuary. A series of 2D numerical model experiments with a set of passive tracers were conducted to study the impacts of spring-neap tidal variation, freshwater inflow, and tidal flat reclamation on the age spatial distribution of pollutants.

Results show that the age changed with the tidal level although a dynamic equilibrium condition was obtained. The age near the southern bank of the Jiaojiang River is less than the age at the northern bank. The age distribution in space showed a tongue-shaped pattern, with low tracer age in the middle of the channel and relatively high tracer age in the shallow areas adjacent to the shoreline.

The age distribution depends on the hydrological condition. The influence of freshwater on the age distribution is more significant in the river channel whereas the influence of spring-neap tide is minor. On the contrary, the tide is the dominant factor in controlling transport processes outside of the estuary, where the river discharge has little effect on the age distribution.

After the reclamation, the age in the mouth of the estuary and around the tidal flats had increased by up to 5 days. Under mean flow condition, the tongue-shaped pattern of the age distribution near the mouth of the estuary has become clearer, suggesting that more pollutant is discharged out of the estuary through the center of the channel without the presence of tidal flat. The tidal flat reclamation has almost no influence on the mass transport in the river channel.

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