The cumulative effect of the perennial reclamation projects on water exchange in Sanmen Bay

P Y Huang¹,4, H Hu² and M M Zhang³

¹Key Laboratory of Engineering Oceanography, Second Institute of Oceanology, Ministry of Natural Resources, Hangzhou 310012, China
²National Ocean Technology Center, Tianjin 300112, China
³North China Sea Environmental Monitoring Center, Ministry of Natural Resources, Qingdao 266033, China

E-mail: syhjjhpy@163.com

Abstract. Sanmen Bay is located in the middle of Zhejiang coastal area. It is a semi-enclosed bay with many silty tongue-like shoals. There are also harbors with good water depth. This form of shoals and branches constitutes a unique muddy coastal landform on the Zhejiang-Fujian coast. Large areas of tidal flats provide conditions for reclamation. Since the beginning of the new millennium, the speed of reclamation in Sanmen Bay has accelerated, and its cumulative impact on the environment has gradually increased. Based on the high-resolution water depth and coastline data of 2003 and 2013, this paper establishes a numerical model based on Delft3D to study the cumulative response of hydrodynamics, tidal prism, and water exchange capacity to the reclamation project in a decade. The calculation results show that within ten years, the reclamation of the sea has reduced the area of the shoal in Sanmen Bay. The trend of the ebb current in the bay has been weakened, and the tidal prism has been reduced by nearly 7%. Also, the reclamation projects have weakened the overall water exchange capacity of Sanmen Bay with the outside world. Due to the topographical features of Sanmen Bay, the degree of influence varies from region to region.

1. Introduction

The bay is an important geographical unit at the junction of the sea and the land, and an important base for human beings to engage in marine economic activities and develop tourism. As one of the three major bays in Zhejiang, Sanmen Bay is located in the middle of China's “Golden Coastline.” As a typical semi-closed strong tide bay, large areas of tongue-like tidal flats interlace with port branches and form shapes like palms, which has always been studied by researchers.

With the rapid development of China's economy, the construction of the marine economy is in full swing, and the contradiction of land use has become increasingly prominent. As a result, a large number of reclamation projects have occurred in coastal areas. The reclamation project changes the shape of the shoreline and the active water area of the sea area, thereby changing the hydrodynamic sediment environment around it. Therefore, the reclamation provides a large amount of land and causes various engineering, environmental, and ecological problems at the meantime. The cumulative effect of large-amount, large-scale, and continuous reclamation activities is particularly significant. There are many studies on the impact of reclamation projects on the water environment of the bay [1-8]. Many bays such as China's Jiaozhou Bay, Quanzhou Bay, Shenzhen Bay, Japan's Tokyo Bay and San Francisco Bay have caused a series of problems, such as weakened hydrodynamic field, reduced...
water exchange capacity, eutrophication and deterioration of the Gulf ecological environment, among which the development of tidal flat resources is one of the leading causes of these problems. In Zhejiang Province, Zeng et al. [9] established numerical models for different years in Xiangshan Port to study the accumulative effects of several reclamation projects in Xiangshan Port on the tidal volume, flow field, water level, and water exchange capacity over a long period. Luo [10] established a convective diffusion model to study the effects of the discharge of aquaculture wastewater after the reclamation of Xiayangtu. Xu et al. [11] took the reclamation projects in Xupantu and Xiayangtu as examples, and discussed the influence of these two reclamation projects on tidal flow velocity in the bay. Based on the primary data, the paper firstly establishes and validates the Sanmen Bay numerical model for the two years of 2003 and 2013, and then calculates the hydrodynamic environment elements of the two models in the same period in 2013. Thus, the cumulative effect of the reclamation project on the water exchange in Sanmen Bay during the ten years is studied.

2. Sanmen Bay reclamation history
The total area of the Sanmen Bay tidal flat is 295 km², accounting for 38% of the Sanmen Bay sea area (775 km²). According to the water conservancy, reclamation in Sanmen Bay had been started early from the Tang to Song dynasties. Moreover, there are records of tidal fields and salt pans in Yuan and Ming dynasties. In the late Ming and early Qing dynasties, with the needs of production and development, the reclamation and ponding had entered the development period. After the founding of the People's Republic of China, the high shoal reclamation and the port containment were successively started. So far, the Sanmen Bay has been reclaimed (including the water surface area in the port) with an area of 332,000 mu (221.6 km²), accounting for 28.6% of the total area of the Sanmen Bay and 75.1% of the tidal flat area. For more than 60 years, the reclamation has occupied an average of 4.7% of Sanmen Bay sea area per decade and 12.3% of the total area of Sanmen Bay tidal flat. Among them, the reclaimed area from 2003 to 2013 is about 100,000 mu, accounting for about 30% of the total reclaimed area. It is a period of the rapid increase in the area of the reclamation. The specific distribution is shown in figure 1. The reclamation areas of Xiayangtu, Shepantu, and Yanzhantu are relatively large, totaling more than 90,000 mu. These large-scale reclamation projects are located in the top shoal of Sanmen Bay.

![Figure 1. Distribution of Sanmen Bay reclamation in 2003-2013.](image)
3. Establishment and verification of model

3.1. Calculation range and method

The shoreline data used in the model was obtained based on the digitization of the satellite images of the year. The topographic data is obtained from a wide range of surveys due to the construction needs of a certain project in the Bay. Some of the sea areas have no measured water depth data, and the chart data is used, and the elevation is unified.

The calculation range includes the entire Sanmen Bay and is appropriately extended eastward to set the boundaries. Based on Delft3D, the orthogonal curve meshing domain is used to calculate the domain, that is, by establishing a large-scale, locally refined model, and using the dense distribution of the mesh to achieve large-scale and local-fine simulation. At the same time, the mesh generation technology can control the smoothness, orthogonality, and sparse distribution of the mesh, and the complex terrain of the research area can be well simulated. There are 792 meshes in the east-west direction, 401 meshes in the north-south direction, and 192,601 nodes. The minimum length of the mesh is about 50 m, which can describe the island and coastline contours (figure 2). The calculation time step is 2.5 min. Equations are discretized by using the ADI method. The treatment of the open bay is also called the treatment of the dynamic boundary. In this paper, the “dry and wet” method of floodplain treatment is used to define a water depth $h=0.01$ for the dry and wet mesh judgment in the model. When $h<0.01$, the speed is 0, while the momentum equation is no longer solved to determine the velocity component of the control body.

![Computational mesh and observatory](image_url)

**Figure 2.** Computational mesh and observatory.

The control equation uses a shallow water tidal wave equation with a vertical eddy integral containing horizontal vortex viscous terms. A curved mesh segments the computational domain. Compared with the general rectangular mesh, the curved mesh can be better close to the boundary, so that the flow state at the boundary can be better simulated and the computational impact caused by the boundary is reduced.

3.2. Calculation range and method

Vertical average mass conservation equation:
\[
\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi \xi}}/G_{\eta \eta}} \frac{\partial [(d + \zeta)U]\sqrt{G_{\eta \eta}}}{\partial \xi} + \frac{1}{\sqrt{G_{\xi \xi}}/G_{\eta \eta}} \frac{\partial [(d + \zeta)V]\sqrt{G_{\xi \xi}}}{\partial \eta} = Q
\]  
(1)

Where \( Q \) represents the role of source and sink, such as drainage, precipitation, and evaporation.

\( \zeta \)-direction momentum conservation equation:
\[
\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi \xi}}/\sqrt{G_{\eta \eta}}} \frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta \eta}}} \frac{\partial u}{\partial \eta} + \frac{uv}{\sqrt{G_{\xi \xi}}/\sqrt{G_{\eta \eta}}} \frac{\partial G_{\xi \xi}}{\partial \eta} - \frac{v^2}{\sqrt{G_{\xi \xi}}/\sqrt{G_{\eta \eta}}} \frac{\partial G_{\eta \eta}}{\partial \xi} = -f v
\]

\[
= -\frac{1}{\rho_0 \sqrt{G_{\xi \xi}}} P_\xi + F_\xi + M_\xi + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left( v \frac{\partial v}{\partial \sigma} \right)
\]

\( \eta \)-direction momentum conservation equation:
\[
\frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi \xi}}/\sqrt{G_{\eta \eta}}} \frac{\partial v}{\partial \xi} + \frac{v}{\sqrt{G_{\eta \eta}}} \frac{\partial v}{\partial \eta} + \frac{uv}{\sqrt{G_{\xi \xi}}/\sqrt{G_{\eta \eta}}} \frac{\partial G_{\xi \xi}}{\partial \eta} - \frac{u^2}{\sqrt{G_{\xi \xi}}/\sqrt{G_{\eta \eta}}} \frac{\partial G_{\eta \eta}}{\partial \xi} = -\frac{1}{\rho_0 \sqrt{G_{\eta \eta}}} P_\eta + F_\eta + M_\eta + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left( v \frac{\partial v}{\partial \sigma} \right)
\]

The \( \sigma \) coordinates are used in the vertical direction. Under the \( \sigma \) coordinates, the vertical velocity component is solved by the mass conservation equation:
\[
\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi \xi}}/\sqrt{G_{\eta \eta}}} \frac{\partial [(d + \zeta)U]\sqrt{G_{\eta \eta}}}{\partial \xi} + \frac{1}{\sqrt{G_{\xi \xi}}/\sqrt{G_{\eta \eta}}} \frac{\partial [(d + \zeta)V]\sqrt{G_{\xi \xi}}}{\partial \eta} + \frac{\partial \omega}{\partial \sigma} = H(q_{in} - q_{out})
\]

Here, \( \omega \) refers to the vertical velocity perpendicular to the \( \sigma \) coordinate plane, which changes as the \( \sigma \) coordinate plane moves up and down.

In the above formulas, \( H \) is the water depth, \( H = h + \zeta \), \( \zeta \) is the water level, \( h \) is the water depth relative to the mean sea level; \( G_{\xi \xi} \) and \( G_{\eta \eta} \) are the conversion coefficients of the curve coordinate system converted to the Cartesian coordinate system; \( U \) and \( V \) are the average flow velocity in the \( \xi \) and \( \eta \) directions; \( g \) is the gravitational acceleration; \( f \) is the Coriolis force parameter; \( F_\xi \) and \( F_\eta \) are the turbulent momentum flux in the \( \xi \) and \( \eta \) directions; \( P_\xi \) and \( P_\eta \) are the water pressure gradient in the \( \xi \) and \( \eta \) directions; \( M_\xi \) and \( M_\eta \) are the source and sink of momentum in the \( \xi \) and \( \eta \) directions; \( q_{in} \) and \( q_{out} \) represent source/sink terms.

### 3.3. Boundaries and parameters

The water boundary control is adopted for the open boundary, and the three open boundaries of the south, north and east are set, and the water level calculated by the regional large model is used for driving. The large model boundary is provided by the global tidal wave model TPX06. It is driven by eight tidal constituents, which are \( M_2, S_2, N_2, K_2, K_1, O_1, P_1 \) and \( Q_1 \). It can construct the real astronomical tide process in the deep water of the open sea. The other boundaries are fixed boundaries and no water flows are exchanged. The gravity acceleration is 9.81 m/s\(^2\), the seawater density is 1025 kg/m\(^3\), and the horizontal eddy viscosity coefficient is 25 m/s\(^2\). The seafloor roughness coefficient sensitive to the calculation results is characterized by the Manning coefficient according to the regional characteristics and calculated by using the empirical formula having good application effect in this region, i.e., \( m = 0.015 + 0.00255x^{0.15 \cdot \text{depth}} \), where \( m \) is the Manning coefficient and the depth is the actual water depth at the grid.

### 3.4. Model verification

For the numerical models corresponding to the shoreline topography in 2003 and 2013, the tidal level, flow rate, and flow direction are verified respectively to evaluate the reliability of the model. The measured hydrological data used for verification was collected on-site for the construction of a project. Figures 3 and 4 show (specific location is shown in figure 2) tidal level verification chart from October 24, 2003, to October 31, 2003, and July 25, 2013, to August 1, 2013. It is indicated that the
measured tide level fits well with the simulation calculation, and the simulation errors of the highest and lowest tide levels are generally within 10 cm, and the phases are basically coincident.

Two stations in the bay are selected to verify the large power vector. Based on the verification results (figures 5 and 6), the single station trend measurement results are compared with the simulation results: the flow direction deviation between rising tides and ebb tides is usually within 10°; the flow velocity difference of between them is generally within 20%. It can also be seen from the flow rate comparison in figures 5 and 6 that compared with 2003, the measured value and the simulated value of the tidal flow velocity at the two stations in 2013 are significantly weakened. In the figure, the peak tends to be horizontal.

By comparing the model verification of the two years of shoreline and terrain, the calculated values of tidal level, flow velocity, and flow direction are basically consistent with the measured values, indicating that the parameters adopted by the model are basically reasonable, the calculation method is reliable, and the motion characteristics of tidal wave in Sanmen Bay can be simulated. Thus, the method can be used for further prediction and research.

Figure 3. Tide level verification (1#).

Figure 4. Tide level verification (2#).
4. Impact analysis of the reclamation project

The reclamation project has two effects on the topography and geomorphology. One is to directly change the shoreline shape and the effective area of the sea area, and the other is to influence the surrounding seabed topography further. These changes will, in turn, change the surrounding hydrodynamic environment, the tidal prism, and the water exchange capacity between the bay and the outside world. The following two models of different years are used to calculate the environmental elements in the same period, and the difference can be considered as the response of each element to the reclamation project.

4.1. Changes in the tidal prism

Due to the tidal phenomenon of the ocean, the amount of seawater that can be accommodated from the low tide to the high tide is called the tidal prism. The amount of tidal prism can directly affect the
degree of exchange between the gulf and the open sea, thus restricting the self-purification capacity of the gulf, so it is essential to maintain the good ecological environment of the gulf. The change of the tidal prism mainly comes from 1) the reclamation of the sea directly occupies the sea area, which leads to the reduction of the water area; 2) the reclamation causes the surrounding terrain to be adjusted accordingly; 3) the influence on the hydrodynamic force also affects the tidal prism.

In this paper, the tidal prism is obtained by calculating the volume difference of seawater contained in Sanmen Bay at high and low tides, and the rate of change of tidal prism in 2013 relative to 2003 is given. It can be seen from table 1 that the reclamation projects reduce the water area in Sanmen Bay, which in turn leads to a decrease in the tidal prism throughout the bay. The change in the amount of tidal prism is the largest at the time of the spring tide, and its decrease value reaches $1.7 \times 10^8$ m$^3$. However, the rate of change is the greatest at middle tide levels, with a reduction of 6.94%.

| Content   | Spring | Middle tide | Neap  |
|-----------|--------|-------------|-------|
| 2003      | 27.1   | 21.6        | 9.07  |
| 2013      | 25.4   | 20.1        | 8.58  |
| Value of variation | -1.7   | -1.5        | -0.49 |
| Rate of variation      | 6.27%  | 6.94%       | 5.4%  |

The change of the tidal prism directly affects the tidal characteristics of the bay. It is related to the rise and fall of the tidal channel of the gulf, affecting the maintenance of the navigation channel in the port area, and may also disrupt the dynamic balance between the hydrodynamic conditions and the bay form, so that the shape of the bay trough will adjust accordingly. It also has an impact on the water exchange capacity of the bay, which in turn affects the water quality in the bay.

4.2. Changes in water exchange capacity

The reclamation projects not only reduce the tidal prism in Sanmen Bay but also change the tidal current. The reclamation between the water branches blocks the exchange of water flow and further affects the water exchange capacity. In order to study the cumulative effect of reclamation projects on water exchange in Sanmen Bay from 2003 to 2013, the Delft3D pollutant tracer model is used to simulate the water exchange process in Sanmen Bay. The calculation method adopted is set as follows: the initial content of the dissolved tracer in the whole field is set to 1, and under the action of the tidal current, it exchanges with the clean water of the dissolved tracer concentration of 0 in the open sea, and the water exchange rate of the bay is calculated by simulating with 12d and 24d as the periods. The seawater exchange rate is defined as (1-average content) x 100%. At the same time, as shown in figure 2, according to the topographical features, Sanmen Bay is divided into three areas: I, II, and III. The I and II areas are located at the top of the bay. In 2003, at high tide, the water flow can pass through the middle tidal flat. However, in 2013, due to the implementation of the reclamation project, the flow path was cut off, and Zone III was located at the mouth of the bay.

In order to facilitate an intuitive understanding of the changes in the concentration of dissolved tracer in the bay under tidal currents, the 1# feature point in Zone I is selected for observation. Figure 7 is a comparison of concentration changes in 2003 and 2013. As can be seen from the figure, in general, the concentration of the dissolved tracer changes periodically with the inflow of clear water outside the bay, and its regularity is closely related to the time and intensity of the tide. For Zone I, the Shepantu encloses the tidal channel between Zone I and Zone II, and the seawater outside the bay enters Zone I through the channel at high tide, thus causing the water exchange capacity of Zone I to be greatly declined. The concentration after 24d increases from an average of about 0.5 to an average of about 0.65.
Figure 7. Dissolved state tracer concentration change at 1# feature point in Zone I.

Figure 8. Distribution of dissolved tracer concentration difference after 24d water exchange.

Figure 8 is a distribution plot of dissolved tracer concentration differences between 2013 and 2003 after 24d. It can be seen from the figure that the reclamation project has the greatest impact on Zone I, and its water exchange capacity is greatly weakened. The influence on Zone II is relatively small, and there is also a difference between the north and the south. The difference in the concentration of the dissolved tracer generally shows the law that the impact on water exchange capacity is greater in the south than in the north. Zone III is located at the bay mouth. On the one hand, it is relatively far from the reclamation project. On the other hand, it can be exchanged directly with the clear water outside the bay. Therefore, the impact is minimal. In general, for Zone I and Zone II with multiple branches at
the top of the bay, the north the branch, the stronger the water exchange capacity, the weaker the cumulative response to the reclamation project, which is mainly related to the morphological characteristics of Sanmen Bay and the tidal characteristics of the nearshore. The tide in Zhejiang offshore is mainly affected by the southeastward Pacific tidal wave system [12]. In addition to the influences of shoreline and topography, it allows the outer seawater to enter the northernmost branch smoothly, resulting in the strongest water exchange capacity. The beam-washing effects of the reclamation project can even improve the water exchange capacity of the area. For the water branches in the south, because the reclamation project blocks the water flow between the branches, the water exchange capacity gradually decreases.

Table 2. Relative water exchange rate of each block and the whole bay in the recent decade /%.

| Exchange time /d | Project     | Zone I  | Zone II | Zone III | Whole Gulf |
|------------------|-------------|---------|---------|----------|------------|
| 12               | Year 2003   | 49.4    | 41.2    | 73.3     | 54.6       |
|                  | Year 2013   | 36.6    | 40.3    | 72.5     | 51.3       |
|                  | Change rate in 2013 relative to 2003 | -25.9 | -2.2 | -1.1 | -6.0 |
| 24               | Year 2003   | 62.8    | 58.5    | 79.9     | 67.2       |
|                  | Year 2013   | 52.5    | 59.7    | 79.4     | 65.1       |
|                  | Change rate in 2013 relative to 2003 | -16.4 | 2.0 | -0.6 | -3.1 |

Table 2 shows the average water exchange rate and relative change rate of each block of Sanmen Bay and the whole bay in the recent decade calculated from the dissolved tracer concentration distribution data.

It can be seen from the table that the impact of the reclamation of Sanmen Bay on its total water exchange rate is quite obvious, especially in the short term. Under the coastline and topography in 2003, the average water exchange rate of the whole bay after exchange for 12d and 24d is 54.6% and 67.2%, respectively. Under the coastline and topography in 2013, the average water exchange rate of the whole bay after exchange for 12d and 24d is 51.3% and 65.1%, respectively. Compared with 2003, the relative reduction rates are 6.0% and 3.1%, respectively. Also, compared with the change data of Sanmen Bay tidal prism in Table 1, in general, the average water exchange rate change after 12d is similar to the change rate of the tidal prism.

Due to its semi-closedness and narrowness, Sanmen Bay has relatively limited water exchange capacity. The surrounding reclamation projects have a great influence on it, and its degree shows a certain regularity in space. In the calculation of this paper, the existence of the exposed floodplain is considered, and the shoal is not deepened so that it may be more conservative than other results. In the actual study, if the upstream freshwater input is considered, the water exchange rate in each zone will increase.

5. Conclusion

In order to study the cumulative effect of reclamation projects on the water exchange capacity of Sanmen Bay during the decade of 2003-2013, this paper establishes a numerical model based on the topography and shoreline data of 2003 and 2013 respectively. The various elements of the hydrodynamic environment in the same period is calculated, compared, and analyzed:

- From 2003 to 2013, several large-scale reclamation projects were carried out in Sanmen Bay, which had a certain impact on the hydrodynamic environment. According to the measured data and simulation results, compared with 2003, the 2013 tidal flow velocity advantage was significantly weakened.
- The reclamation project directly reduces the tide space, so that the tidal prism decreases, and the change of the tidal prism is the largest at the time of the spring tide, and the decreased value reaches $1.7 \times 10^8$ m$^3$. However, the rate of change is the greatest at middle tidal levels, with a reduction of 6.94%.
- On the one hand, the reclamation projects will reduce the amount of tidal prism in Sanmen
Bay, which will affect the water exchange capacity. On the other hand, due to the morphological characteristics of the Sanmen Bay shoal and branches, the reclamation will directly block the exchange of water between the water branches and has a further impact on the local waters. According to the calculation results, the impact of reclamation on the water exchange capacity of various regions in the bay is different. Among them, the bay mouth is directly connected to the open sea, and its water exchange capacity is also the strongest, with the least impact. At the top of the bay, based on the topography and the water flow characteristics, the reclamation has little impact on the northern water branch while has a large impact on the southern water branch.

Acknowledgments
This research was supported by projects from the National Science Foundation of China (51179169), Fundamental Research Funds for the Second Institute of Oceanography, SOA (JG1307).

References
[1] Zhang W, Tang J and Liang B 2017 Numerical study on the influence of the forebay reclamation on pollutant transport in the Jiaozhou Bay Mar. Environ. Sci. 36 29-42
[2] Tian Y, Yu D Y and Li Y L 2018 Research on the accumulation of marine environment in Laizhou Bay Period. Ocean Univ. China 48 117-24
[3] Li X J, Zhou Z Q, Chen L L, Li B Q, Liu T T, Ai B H, Yang L F, Liu B and Wang S S 2017 Effect of coastal reclamation on benthic macrofauna in coastal area of Caofeidian, Bohai Bay Oceanol. Limnol. Sin. 48 617-27
[4] Furukawa K and Okada T 2006 The Enviromental in Asia Pacific Harbours Tokyo Bay: Its Environmental Status-Past, Present, and Future ed Wolanski E. (Dordrecht: Springer) chapter 2 pp 15-34
[5] Takekawa J Y, Woo I and Spautz H 2006 Environmetal threats to tidalmarsh vertebrates of the San Francisco Bay estuary Stud. Avian Biol. 32 176-97
[6] Guo W, Li S H and Mao L 2007 A model for enviromental impact assessment of land reclamation China Ocean Eng. 21 343-54
[7] Zhang W, Tang J and Liang B C 2017 Numerical study on the influence of the forebay reclamation on pollutant transport in the Jiaozhou bay Chin. J. Mar. Environ. Sci. 36 29-36
[8] Zhou L L, Huang J O and Zhu Y 2017 Analysis on Changes in Coastline and Reclamation and its Causes Based on 40-year Satellite Data in Jiaojiang-Taizhou Bay Geol. Rev. 63 337-8
[9] Zeng X M, Guan W B and Pan C 2011 Cumulative influence of long term reclamation on hydrodynamics in the Xiangshangang Bay J. Mar. Sci. 29 73-83
[10] Luo X M 2006 Prediction of impact of breeding wastewater discharging on water environment J. Mar. Sci. 24 39-48
[11] Xu X F and Yang T Z 2006 Mathematical model study on overall impact of Sanmenwan Bay reclamation project J. Mar. Sci. 24 49-59
[12] Hu F X and Cao P K 1981 Characteristics of the tidal wave movement in the Sanmen Bay and its relationship with the topographic development Oceanol. Limnol. Sin 12 25-234