Investigating the impact of Xuanmen Project on water residence time in the Yueqing Bay

Xinwen Li1,*, Chao Ying1,2, Yong Liu1 and Wenwei Yao1

1Zhejiang Institute of Hydraulics & Estuary, 50 East Fengqi Road, Hangzhou, China
2College of oceanography, Hohai University, 1 Xikang Road, Nanjing, China
lixw@zjwater.gov.cn

Abstract. A 2D numerical model was used to investigate the impact of Xuanmen Project on water residence time in Yueqing Bay. Three model scenarios were designed to calculate the residence time. The WRT of CASE00 was obviously smaller than that of CASE01 and CASE02. While the WRT of CASE01 and CASE02 was relatively comparable. As for the individual scenario, the WRT increased from the bay mouth to the bay head. In CASE00, The average WRT of the outer bay, middle bay and inner bay was 21.6, 38.5 and 50.6 days, respectively. The average WRT of the entire bay was 32.7 days. In CASE01, a significant increase of WRT was observed in the entire bay. The average WRT of the entire bay was 46.1 days. The WRT increased about 10 days in the lower bay and 20 days in the northern bay compared to CASE00, indicating a significant impact of the Xuanmen Dam. In CASE02, the average WRT of the entire bay was 48.2 days. The WRT increased less than 5 days compared to CASE01, implying that the land reclamation had a minor impact on the WRT of the Yueqing Bay. The flushing homogeneity curve (FHC) was used to study the spatial characteristic of flushing. The steepest curve occurred in CASE00 and the flattest curve occurred in CASE02, implying an increased inhomogeneity due to Xuanmen Project.

1. Introduction

The Yueqing Bay is situated at Zhejiang of China and lies on the western coast of East China Sea. Since 1960s massive anthropogenic projects have been conducted in the bay. These projects include fishery, power plant, dam construction and land reclamation. Due to the impacts above, Environmental reports demonstrate that the ecosystem and water quality of bay has continuously kept deteriorating since the 1980s[1]. In addition, fishery output has also been decreasing as a result of worsening ecosystem. Furthermore, the strength of tidal dynamics has direct impacts on the water quality of the bay due to its transport process and exchange of water with outer sea. Consequently, it is urgent to understand the tidal dynamics and water exchange characteristics of the bay.

Pollutants are generally easy to be transported out in bays with strong tidal dynamics and large tidal flux. In contrast, it is difficult for the pollutants to move to outer sea in bays with weak tidal current and small tidal flux. It is important to know the timescale for pollutants and nutrients discharged into the bay to be transported out of it through the bay mouth for managers and ecologists. To this end, Various timescales developed by different researchers to assess the assimilative capacity of a water body and to quantify the transport processes, among which residence time(RT), water age[2], turnover time, transit time and flushing time are widely used. However, different authors often referred the same timescale to different definitions and formulations in terms of calculations[3,4]. Some researchers have paid attentions to this matter. Zimmerman[5] introduced the concept of residence time.

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time and defined it as the remainder of the lifetime of a particle considered. Bolin and Rodhe[6] summarized previous results and introduced a more rigorous definition for the concept of turnover time, water age and transit time. Takeoka[7] summarized previous works and introduced the residence time as analogous to the definition of age and transit time.

As shown in Figure 1, the Yueqing Bay features calabash shape and is semi-enclosed. Its width is 3.5 km in the middle and increases to 16 km at the bay mouth. Bottom bathymetry of the bay is complex with both tidal channel and tidal flat layout. The tidal channel with depth larger than 70m lies on the eastern coast and the tidal flat with datum above 0m lies on the western coast in the southern bay. Whereas in the northern bay, tidal channel, tidal flat and islands lie among each other. Furthermore, The bay features macrotidal with a tidal range that increases from 4.66 m at the lower mouth to 8.53 m at the upper bay[8].

![Figure 1. Bottom bathymetry and location of the Yueqing Bay.](image-url)
2. Methods

2.1. Model description

The residence time was first defined by Zimmerman[5] as the time elapsed since material was first injected into water body to its arrival at the outlet. The definition can be used with certain amount of material element. Takeoka[7] further developed the definition and introduced the remnant function. The final residence time can be obtained through the following integral:

\[ \tau_r = \int_0^\infty \frac{R(\tau)}{\tau_0} d\tau = \int_0^\infty r(\tau)d\tau \]  

in which \( r(\tau) = \frac{R(\tau)}{R_0} \) was called remnant function[7]. In this study, the water residence time (WRT) with spatial variation was calculated with tracer transport equation:

\[ \frac{\partial c(t, x)}{\partial t} + \nabla (uc(t, x) - K\nabla c(t, x)) = 0 \]  

where \( t \) is time, \( x \) is coordinate, \( u \) is the velocity field, \( c \) is the dye concentration and \( K \) is the diffusivity tensor.

In the definition of Takeoka, water residence time for a specified material could be obtained through integrating the concentration time series in the whole bay. Furthermore, the transport model above was forced by tidal current which was simulated with depth-averaged 2D shallow water equations. The set of equations were solved with numerical model. The model was discretized with triangle meshes and solved with finite volume method. The average mesh size in the Yueqing Bay was 200 m and increased to 5000 m at the open ocean boundary. The average time step was 1s.

2.2. WRT calculation

For ideal case, the integral in equation (1) could only be stopped until the result get close to a constant value. This was generally impossible in real case. To this end, a criteria was used to help identify the condition when the integral could be stopped. For each model case, the simulation was conducted until a relative error for every model mesh of the computational domain was smaller than a critical value, \( \tau_{cr} \). In this study, the \( \tau_{cr} \) was set to 0.001[2,9,10] in this study.

3. Calculation of residence time

3.1. Model setup

The detailed model configuration and model calibration can be referenced to Ying, et al.[11] and Ying, et al.[12], which will not be presented in this study.

3.2. Model scenarios

The Xuanmen Project constitute of two stages as shown in figure 2. During Xuanmen Stage I, a dam which connected the Yuhuan Island and the mainland was built. The Xuanmen Dam intercepted the exchange of water between the Yueqing Bay and the Xuanmen Bay which faces the open ocean. The Stage I was finished in 1977 and since then the Yueqing Bay became a semi-enclosed bay. Xuanmen Stage II was implemented with land reclamation in the west of the dam. The land reclamation resulted in decrease of tidal prism of the Yueqing Bay.

The objective of this study is to investigate the impact of the Xuanmen Project on water residence time in the Yueqing Bay. Three model cases were thus conducted as shown in Table 1. CASE00 represented the base model run, in which the Yueqing Bay was connected with the outer open ocean.
through both the southern bay month and the channel in Xuanmen Bay. In CASE01, Xuanmen Stage I had been finished and the channel was intercepted. The Yueqing Bay could only exchange water with outer open ocean through the southern bay month. In CASE03, the water area in the west of the Xuanmen Dam was reclaimed which resulted in a decrease of tidal prism. In all the three model cases, the tracers were injected in the Yueqing Bay (as shown in Figure 3 the area enclosed by S01, Xuanmen Dam in Figure 2 and land) after a spin up of 30 days to get a dynamically steady state. The model period last for six months with output per 10 minutes. The water residence time was then calculated according to equation (6) based on the above model results.

| case name   | short description       |
|-------------|-------------------------|
| CASE00      | Base scenario, no project|
| CASE01      | Xuanmen I               |
| CASE02      | Xuanmen I+ Xuanmen II   |

Figure 2  Layout of the Xuanmen Project (The cross sections will be used in the following part)
4. Results and Discussion
Spatial distribution of residence time of the three model cases were showed in Figure 4. It can be seen that the WRT of CASE00 was obviously smaller than that of CASE01 and CASE02. While the WRT of CASE01 and CASE02 was relatively comparable. As for the individual scenario, the WRT increased from the bay month to the bay head. In CASE00, the WRT around Ximen Island was 50 days and decreased to 40 days around Maoyan Island. The WRT further decreased to 30 days at the cross section of Dashuiwan-Lianyu and about 20 days at the bay month. The average WRT of the outer bay, middle bay and inner bay was 21.6, 38.5 and 50.6 days, respectively. The average WRT of the entire bay was 32.7 days. In CASE01, a significant increase of WRT was observed in the entire bay. The 70, 60 and 50 days isolines lay north of Ximen, Maoyan and Jiangyan Island, respectively. The average WRT near the bay month was about 30 days. The average WRT of the outer bay, middle bay and inner bay was 21.6, 38.5 and 50.6 days, respectively. The average WRT of the entire bay was 32.7 days. In CASE02, The residence time decreased from more than 80 days at the bay head to 20 days at the bay month. The 70, 60 and 50 days isolines lay south of Ximen, Maoyan and Jiangyan Island, respectively. The average WRT of the outer bay, middle bay and inner bay was 30.6, 60.5 and 73.8 days, respectively. The average WRT of the
entire bay was 48.2 days. The WRT increased less than 5 days compared to CASE01, implying that the land reclamation had a minor impact on the WRT of the Yueqing bay.

Furthermore, it was noticeable that the distribution of RT was uniform in the transverse section above Lianyu-Dashuiwan and a different longitudinal distribution was observed below the section. The RT of the eastern bay was larger than that of the western bay. This pattern could be attributed to the bottom topography of the Yueqing Bay. As shown in Figure 1, In the lower part of the bay, the water depth of the eastern part was greater than 10 m with a tidal channel, whereas the water depth of the western part was less than 3 m with vast tidal flat. For the reason above, strong tidal current developed along the eastern part and pollutants was prone to be transported out of the bay through this tidal channel.

![Figure 4. Spatial distribution of residence time.](image)

| Location       | Outer bay | Middle bay | Inner bay | Whole bay |
|----------------|-----------|------------|-----------|-----------|
| CASE00         | 21.6      | 38.5       | 50.6      | 32.7      |
| CASE01         | 30.1      | 55.7       | 67.4      | 46.1      |
| CASE02         | 30.6      | 60.5       | 73.8      | 48.2      |
The spatial distribution of residence time generally indicated that the flushing characteristic was inhomogeneous. The flushing homogeneity curve (FHC) [13] was thus adopted to obtain a better understanding of the flushing characteristic of the Yueqing Bay. The FHC was calculated through summarizing the statistical area percentage of residence time. A steeper FHC in general indicates less variation of flushing characteristic in the Yueqing Bay and a vertical FHC implies that the bay is completed mixed. The FHC for the three model runs was presented in Figure 5. As can be seen in Figure 5, it takes about 47.5, 64.9 and 71.3 days to flush out 90% of the bay and 17.2, 21.5 and 23.3 days to flush out 10% of the bay for the three model case. The time to flush out 50% of the bay was 33.2, 48.9 and 51.0 days for the three model case. The steepest curve occurred in CASE00 and the flattest curve occurred in CASE02, implying an increased inhomogeneity due to Xuanmen Project.

5. Conclusions
In this study, a 2D numerical model was adopted to study the impact of Xuanmen Project on water residence time in Yueqing Bay. Three model scenarios were implemented to calculate the residence time. The first scenario (CASE00) represent the stage before the Xuanmen Project. The second scenario (CASE01) represent the stage after construction of Xuanmen Dam and the third scenario (CASE02) represent the stage after land reclamation in the west of Xuanmen Dam. The WRT of CASE00 was obviously smaller than that of CASE01 and CASE02. While the WRT of CASE01 and CASE02 was relatively comparable. As for the individual scenario, the WRT increased from the bay mouth to the bay head. In CASE00, the average WRT of the outer bay, middle bay and inner bay was 21.6, 38.5 and 50.6 days, respectively. The average WRT of the entire bay was 32.7 days. In CASE01, a significant increase of WRT was observed in the entire bay. The average WRT of the entire bay was 46.1 days. The WRT increased about 10 days in the southern bay and 20 days in the northern bay compared to CASE00, indicating a significant impact of the Xuanmen Dam. In CASE02, the average WRT of the entire bay was 48.2 days. The WRT increased less than 5 days compared to CASE01, implying that the land reclamation had a minor impact on the WRT of the Yueqing bay. The FHC curve was adopted to study the flushing homogeneity of the Yueqing Bay. The results demonstrated that it take about 47.5, 64.9 and 71.3 days to flush out 90% of the bay and 17.2, 21.5 and 23.3 days to flush out 10% of the bay for the three model case. The steepest curve occurred in CASE00 and the flattest curve occurred in CASE02, implying an increased inhomogeneity due to Xuanmen Project.
Acknowledgments
The study was financially supported by the National Key R&D Program of China (2018YFC0407505).

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