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Study on water exchange capacity of Fangcheng Bay in dry and wet season based on MIKE3 model

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ABSTRACT

In order to have a comprehensive understanding of the water exchange capacity in Fangcheng Bay, a high-resolution numerical model named MIKE3, which is a three-dimensional hydrodynamic model, is established based on unstructured triangular grid. Using Lagrange proton tracing method, the half-exchange period and commutative law of water are selected as the evaluation indexes to evaluate the water exchange capacity of Fangcheng Bay in dry and wet seasons. The results are shown as follows: the water exchange in Fangcheng Bay is mainly controlled by runoff and tide. Due to the existence of Fangcheng River, the spatial distribution of the concentration of conservative particles in the West Bay increased from the estuary to the outside of the bay, while that in the East Bay increased from the entrance to the inside of the bay. With the increasing time, the decrease ratio of concentration in the two bays reduces. The water exchange time in West Bay is obviously shorter than that in East Bay. The half-exchange period of West Bay is 1.7 d in wet season and 3.6 d in dry season, while that in East Bay is 15.2 and 27.8 d, respectively.

Keywords: MIKE3; Water exchange; Half-exchange period; Water exchange ratio

1. Introduction

Fangcheng Bay is located in Guangxi Province, China. The characteristics of monsoon are obvious. It is vulnerable to disastrous weather, such as typhoon. And it is divided into East Bay and West Bay. The two bays are separated by land and connected by long and narrow waterway. The bay is surrounded by the central city, with dense population and developed industry. A large amount of sewage is discharged into the bay every year. And these pollutants have significant impacts on marine ecology and human health. Because of the existence of Fangcheng River, most of the sewage outlets are located in West Bay. The capacity of water exchange is an important index to evaluate the environmental capacity of the bay, which represents the capacity of physical self-purification, and the water quality in the bay is directly related to the strength of exchange capacity [1]. Under the conditions of runoff and tidal power, the study of water exchange capacity in the East and West Bay of Fangcheng should be carried out to form a scientific understanding of the exchange capacity, leading to formulate reasonable countermeasures and to reduce the impact on the ecological environment, which is of great scientific significance for the rational development and utilization of two bays in Fangcheng in the future.

Water exchange refers to the mixing of water through physical processes such as convection and diffusion. In the

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study of water exchange in gulf and nearshore waters, the speed of water exchange is generally described by defining various time scales that can be represented by half-exchange period, exchange ratio and retention time, etc. Box model [2,3] is the earliest research method for water exchange capacity. With the development of numerical model, convection–diffusion model [4] and Lagrange particle track [5] have gradually become the main methods to study water exchange. In order to explore the capacity of water exchange, Garvine [6] constructed a three-dimensional numerical model of ECOM and conducted a large number of experiments to represent the water exchange on the ideal continental shelf. Berdeal et al. [7] used ECOM3D to simulate the water exchange in Columbia River, where high flux exists. Chao and Boicourt [8] adopted three-dimensional model to simulate water exchange in Chesapeake Bay, founding that the vertical mixing will promote water exchange. Fong and Geyer [9] showed that the fresh water in Chesapeake Bay and Delaware Bay will appear on the right of the bay and the downstream through the mechanism of water exchange. Zhang et al. [10] simulated water exchange under different wind directions by building non-theoretical models, and found that wind had a greater impact on water exchange. Kourafalou et al. [11] simulated the water exchange of Savannah River with mathematical model, and also pointed out the influence of wind on the process of water exchange. In addition, Kourafalou et al. [12] pointed out that the tide provides energy for water exchange. Cheng and Casulli [13] used unstructured grid model to simulate the dynamic process of water exchange, and the results indicated that astronomical tide affected water exchange greatly, especially in the vertical direction. Establishing a convection–diffusion model based on the Lagrangian data, Fiammetta et al. [14] found that the current and wind have an important impact on the water exchange in the Labrador Sea area. Sirjacobs et al. [15] showed the influence of different seasons on water exchange in the Aral Sea by establishing 3D hydrodynamic model.

There are not many studies about water exchange in Fangcheng Bay, Chen and He [16] used traditional methods to calculate the tidal prism of East Bay. Compared with 2008, the reduced tidal prism in East Bay accounted for 5.5% of the total tidal prism in 2012, leading to the weakening of water exchange capacity. Jiang et al. [17] analyzed the influence of the land reclamation in iron and steel project in Fangcheng City and considered that the changes of current, wave, tidal prism and other factors caused by the land reclamation were small, and the maximum reduction of tidal prism was 8%. The research mentioned above provided good foundations for the research of this paper, in order to have a comprehensive understanding of the water exchange capacity of Fangcheng Bay, this paper built a three-dimensional hydrodynamic numerical model of MIKE3 with a high-resolution unstructured grid. And using Lagrange particle tracing method, this paper selected the exchange ratio and half-exchange period as evaluation indexes to study water exchange capacity of Fangcheng Bay for scientific management in future. Section 2 describes the details about the model and the evaluation index, and the validation of the model and the result are shown in Section 3. Section 4 reports the summary and conclusions.

2. Materials and methods

2.1. Model introduction

MIKE3 developed by the Danish Institute of hydraulics is adopted for simulation in this study, that is, a three-dimensional hydrodynamic model. Compared with MIKE21, this model is more suitable for the simulation study of deep water areas, and is widely used in the study of estuary, coast and ocean [18]. Flow module in MIKE3 uses the standard Galerkin finite element method to discretize the horizontal space, and uses the explicit windward differential scheme to discretize the momentum equation and transport equation in time. The model built by MIKE3 is based on Reynolds averaged Navier–Stokes equation, which satisfies Boussinesq hypothesis and hydrostatic pressure distribution.

2.2. Numerical mode configurations

2.2.1. Simulation area setting

According to the hydrodynamic law in the gulf of Tonkin, the calculation range is determined on the premise that the boundary effect of the calculation area has no effect on Fangcheng Bay. The opening boundary is from Yuntun county of Vietnam to Dafengjiang estuary of Beihai city. The grid is densified in Fangcheng Bay and the estuary of Fangcheng river. The calculation area and grid are shown in Fig. 1. The area is about 150 km long from east to west, and 75 km long from south to north, with a total area of about 50 km^2. The calculation step in the open sea is in the range from 1 to 2 km. The minimum resolution of the grid in the Fangcheng river is about 10 m. There are 31,879 nodes and 59,364 grids. Three sigma layers are set in vertical direction.

2.2.2. Depth and boundary

The original dataset of DBDB5 (Digital Bathymetric Database Version 5.2) provided by the National Center for Geoscience of the United States is used in the open sea, and the electronic chart and survey data are used in the nearshore water. In the process of using the electronic chart, the depth is revised by the relationship between the tide stations and the theoretical lowest tide level.

The land boundary is extracted from the electronic chart, and it is revised by using the survey data and the latest coastline information in Google Earth.

2.2.3. Calculating time-step and bed roughness

The time-step of the model is dynamically adjusted according to the CFL to ensure that the calculation is carried out stably. To ensure the CFL less than 0.8, the minimum time-step is 0.1 s, and the maximum time-step is 120 s.

2.2.4. Model setting

The initial water level in the nodes and the current velocity in the grid are both set as 0. The amplitude, lag angle and current velocity of tide at the open boundary are derived from Tpxo9 dataset, which is released in 2018.

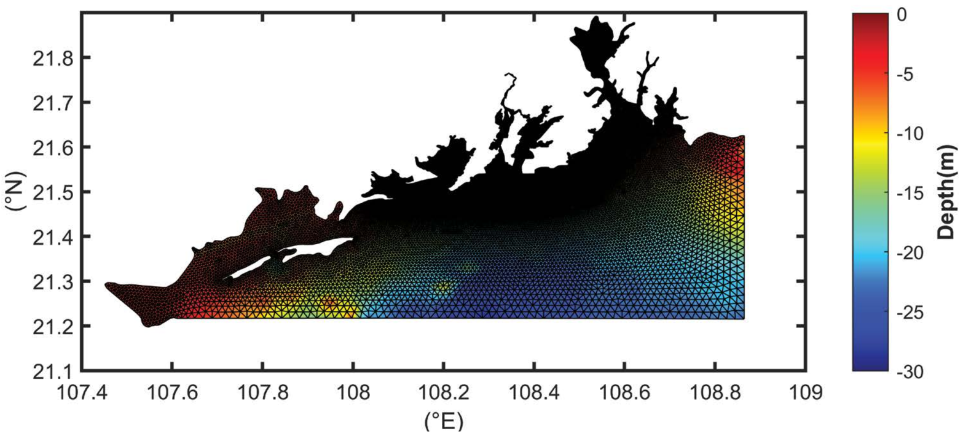

Fig. 1. Triangular system in modeled area and the distribution of depth.

Its accuracy is high in Chinese offshore, including eight basic tidal components (M2, S2, N2, K2, K1, O1, P1, Q1), two long-term tidal components (Mf and Mm), and the components of M4, Ms4, Mn4, 2N2, S1, etc. In this paper, eight tidal components are adopted to run the model in the open boundary.

The runoff and wind are taken as the forced conditions. They are determined according to the statistical data for many years. According to the data of Changqi hydrological station in the middle reaches of Fangcheng River from 1956 to 2004, the multi-year average runoff of the whole basin is 21.05 × 109 m^3, and the multi-year average depth is 2,353.0 mm. The flow in the wet season (from April to October) can reach 99.85 m^3/s, and that in the dry season (from November to March of the second year) can reach 33.28 m^3/s. According to the wind speed data from 1994 to 2014 provided by Meteorological Bureau in Fangcheng City, the average wind speed in the wet season is 2.7 m/s, and that in the dry season is 3.7 m/s.

In this study, the water exchange between the East Bay and the West Bay of Fangcheng City was studied under two conditions. The first condition is in wet season with multi-year average wind in SSW direction with the wind speed of 2.7 m/s, the other is in dry season with multi-year average wind in NNE direction with the wind speed of 3.7 m/s.

2.3. Evaluation index

Water exchange refers to the mixing of water with the surrounding water through physical processes such as convection and diffusion. In the study of water exchange in gulf and nearshore waters, various time scales are generally defined as the evaluation index to describe the capacity or speed of water exchange, such as half-exchange period, exchange ratio, retention time, etc.

2.3.1. Exchange ratio

The exchange ratio of water refers to the ratio of the water in the open sea entering or leaving the bay to the total amount of inflow or ebb during the tide period [19]. Assuming that in a tidal cycle, only runoff is flowing into the boundary of the estuary, and all the substances in the estuary are uniformly dissolved in the seawater, the exchange ratio can be deduced according to the principle of the conservation of matter. Based on the above assumptions, the following formula can be obtained:

$$r_E = \frac{q_0}{Q_F} \tag{1}$$

$$Q_F C_F = q_0 C_0 + q_E C_E \tag{2}$$

While $q_E = (Q_F - q_0)$ is simultaneous with the above two equations, the seawater exchange rate r_E can be obtained as follows:

$$r_E = \frac{C_F - C_E}{C_0 - C_E} \tag{3}$$

where Q_F is the amount of water flowing into the bay at high tide; q_0 is the amount of water flowing into the bay at the first time; q_E is the amount of water that flows out at low tide and returns to the inner bay at high tide; C_B is the average concentration of index substances in the bay; C_0 is the average concentration of index substances out of the bay; C_E is the average concentration of index substance in the effluent at low tide; C_F is the average concentration of the index substance in inlet water at high tide. The ebb tide exchange rate is the proportion of the seawater flowing out of the bay at the ebb tide containing the water in the first outflow of the bay. According to the above assumptions and the conservation of mass, we can get that:

$$r_F = \frac{q_B}{Q_E} \tag{4}$$

$$Q_E C_E = q_B C_B + q_F C_F \tag{5}$$

That $q_E = (Q_E - q_B)$ accompanies with Eqs. (4) and (5) to deduce the exchange ratio of R_F:

$$r_F = \frac{C_F - C_E}{C_F - C_B} \tag{6}$$

where Q_E is the amount of water flowing out of the bay at low tide; q_B is the amount of inner water that the first discharge out of the bay; q_F is the amount of water that returns at high tide and flows out at low tide. Assuming that the seawater in and out of the bay is directly exchanged and considering the phenomenon of tidal inequality, the flow of flood and ebb tide is equal, that $Q_F = Q_E = Q$. According to the conservation of matter, we can get:

$$Q\left(C_F - C_E\right) = Qr_G\left(C_0 - C_B\right) \quad (7)$$

Then, the average seawater exchange rate r_G can be expressed as follows:

$$r_G = \frac{C_F - C_E}{C_0 - C_B} \quad (8)$$

According to Eqs. (3), (6) and (8), it can be obtained that the average exchange rate r_G in a tidal cycle has the following relationship with the exchange rate of r_E in flood tide and r_F in ebb tide:

$$\frac{1}{r_G} = \frac{1}{r_E} + \frac{1}{r_F} - 1 \quad (9)$$

So we can get the exchange ratio of r_G, that is, expressed as $r_G = \frac{r_E \cdot r_F}{r_E + r_F - r_E r_F}$.

2.3.2. Half-exchange period

The half-exchange period of sea water refers to the time when 50% of the water in the bay is exchanged to the outside of the bay under tide and runoff, and it represents the capacity of water exchange in the bay that has been applied in many bays.

Under the influence of ocean dynamics and fresh water constantly injected by runoff and precipitation, it is complex and long for the original water in a bay to be completely exchanged out. If runoff and precipitation are not considered, only considering the action of tide and current, the calculation method of water exchange period is as follows: the total amount of seawater in the bay is Q, and the amount of water brought into the bay during flood tide is the same as the amount of water discharged in the ebb tide during one tidal cycle, that is $Q_0 = Q_B$. After a tidal cycle, the proportion of the remaining original water in the bay to the total water is given as follows:

$$1 - \frac{Q_0 \cdot r_E \cdot r_F}{Q} = a \quad (10)$$

After two cycles, the proportion of the original water remained in the total water in the bay is given as follows:

$$a\left(1 - \frac{Q_0 \cdot r_E \cdot r_F}{Q}\right) = a^2 \quad (11)$$

By analogy, after n cycles, the proportion of the remaining original water in the total water in the bay is given as follows:

$$a^{n-1}\left(1 - \frac{Q_0 \cdot r_E \cdot r_F}{Q}\right) = a^n \quad (12)$$

Assuming that 50% of the sea water in the bay is exchanged after x cycles, then:

$$0.5 = a^x \quad (13)$$

Thus, we can get the cycle number x when 50% of the sea water is exchanged in the bay:

$$x = \frac{\log 0.5}{\log a} \quad (14)$$

The variation of half-exchange period of sea water in different tidal periods is related to the tide, runoff, wind, temperature, salinity and other factors. Therefore, in order to determine the exchange period of sea water in Fangcheng Bay, we should build multiple tidal cycles to calculate the average water exchange ratio and the average half-exchange period.

In this paper, the entrance of the bay is taken as the boundary line between open sea and bay. The conservative particles are released in the middle period of the spring tide. The initial concentrations of the conservative particles in the bay and open sea are set to 1 and 0, respectively. Because of the dynamic effect of the tide, the average concentration of the conservative particles in Fangcheng Bay will change periodically with the tide, and also with the semimonthly periodic change of the spring and neap tide. In this paper, PL64TAP low-pass filter [20] is used to filter out the tidal part, and the change of the concentration of the conservative particles in the East Bay and the West Bay will be calculated, respectively, in the wet and dry seasons. The average values of the water exchange ratio and the half-exchange period are calculated.

3. Results and analysis

3.1. Model validation

In order to verify the validation of the model, the tide level and tidal current are simulated by the hydrodynamic model. The layout of the measured stations of tide level and tidal current is shown in Fig. 2, and the detail information of the stations is shown in Table 1.

3.1.1. Tidal level verification

The model outputs the tide level in the temporary station named Xianrendong from September 29, 2019 to September 30, 2019, the comparison between measured data and simulation data was drawn in Fig. 3. The results show that the model can simulate the process of tide well.

3.1.2. Tidal current verification

Four group of surface tidal current measured at different stations from September 29, 2019 to September 30, 2019 were adopted to verify the simulation results. The compared results are shown from Figs. 4–7. The verification results showed that the simulation results were basically consistent with the measured data, which can better reflect the situation of the tidal current in the research area.

The simulation results showed that the hydrodynamic model established in this paper can truly reflect the actual flow characteristics of Fangcheng Bay, and it can be used for the study of water exchange in this area.

3.2. Characteristics analysis of flow field

The simulation results show that the tidal current is irregular diurnal tide. When the tide is rising, the sea water enters into the bays from the open sea. When the tide is falling, the sea water recedes into the open sea. The velocity of ebb current is greater than that of rising current. The direction of rising current is northward while that of the ebb current is southward. In the process of rising tide, the terrain has a greater binding force in the process of spreading. When tide reaches the south of Yuwan Island, it is divided into two branches, one is flowing along Niutouling to the northwest, and the other is flowing along the Yinbukou River to the northeast. The velocity reaches the maximum near the deep channel of Niutouling. After passing Niutouling and Qisha Peninsula, the tidal current enters into East and West Bay. As the water depth becomes shallow, the resistance increases and the velocity decreases gradually. Whether in the outer bay or the inner bay, the tidal current is affected by the shoreline and the deep channel. Ebb tide is the reverse process of rising tide, and the flow field is similar. At the low tide, the velocity in the northeast and northwest of Yuwan Island is small, and a large area of beach is exposed. In the narrow channel of the West Bay, the speed of tidal current can reach more than 1 m/s, and the maximum velocity of tidal current in the East Bay is about 0.8 to 0.9 m/s, as shown in Fig. 5.

3.3. Water exchange ratio

The changes of the concentration of conservative particles in the East and West bays during the wet and dry seasons are shown in Figs. 6 and 7. According to the analysis of the change of the conservative particles with time,

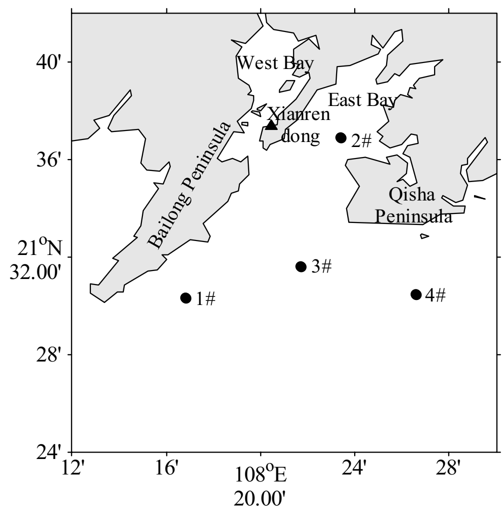

Fig. 2. Locations of tidal stations for the validation of model.

Table 1
Locations of stations for the validation of model

Element	Points	Longitude (°E)	Latitude (°N)	Observation time
Tidal level	Xianrendong	108.340 8	21.622 3	2019.09.29—2019.09.30
Tidal current	1#	108.279 8	21.505 2	2019.09.29—2019.09.30
	2#	108.390 0	21.615 0	
	3#	108.361 3	21.526 3	
	4#	108.442 9	21.507 6	

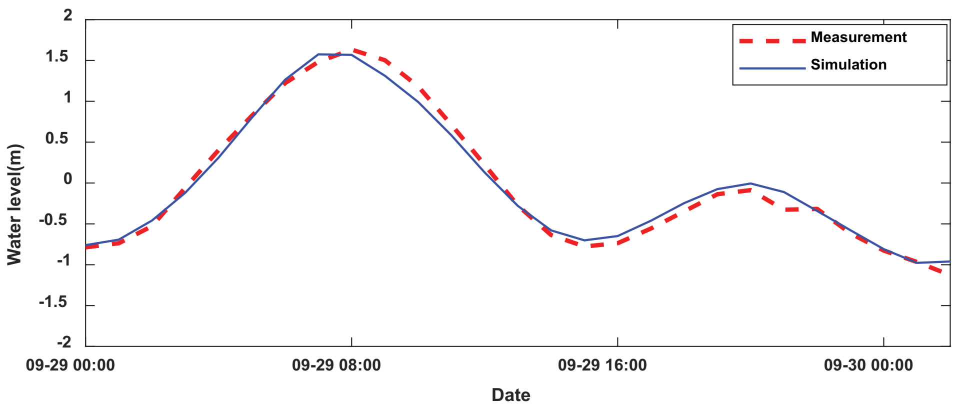

Fig. 3. Water level verification curves in Xianrendong.

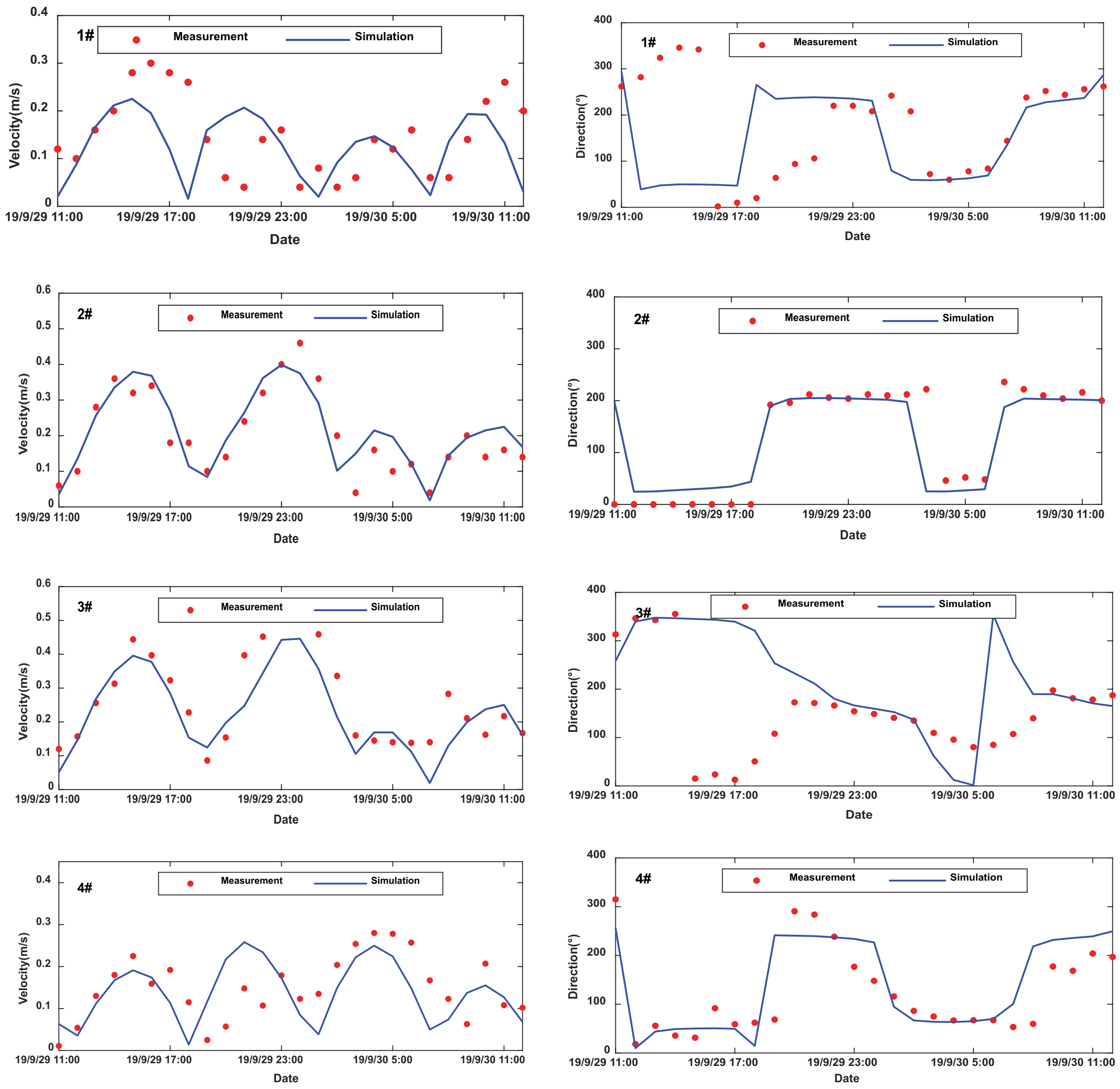

Fig. 4. Surface current verification curves in each stations.

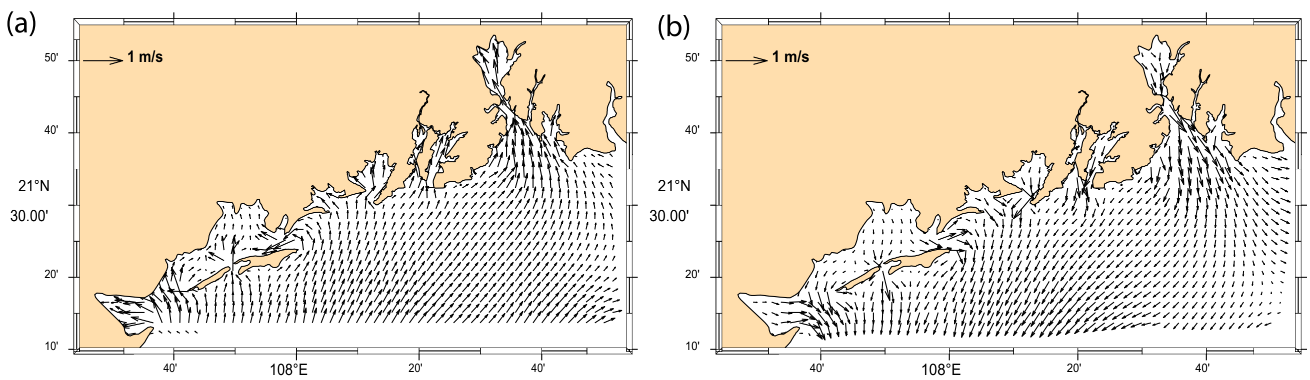

Fig. 5. Flow field of high (a) and low (b) tide during spring period.

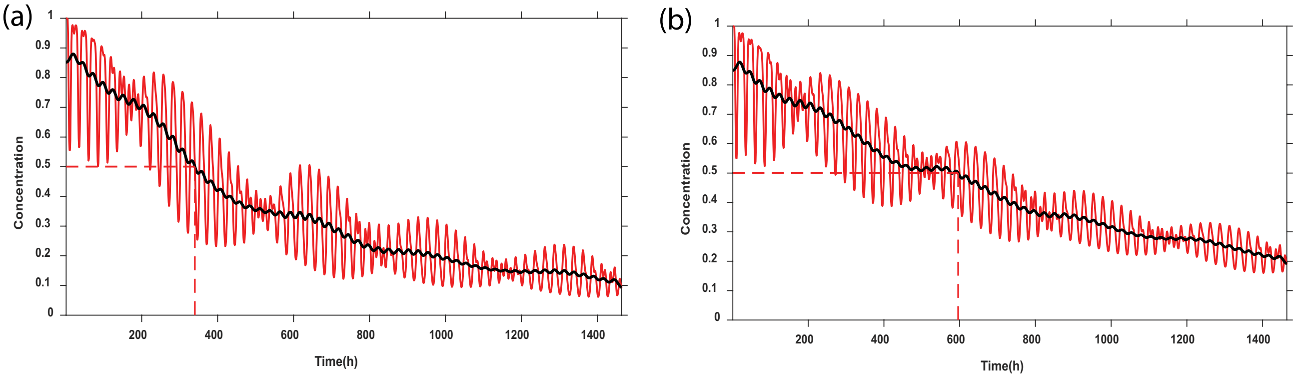

Fig. 6. Variation curve of the concentration of the conservative particle in the East Bay during the wet (a) and dry (b) periods.

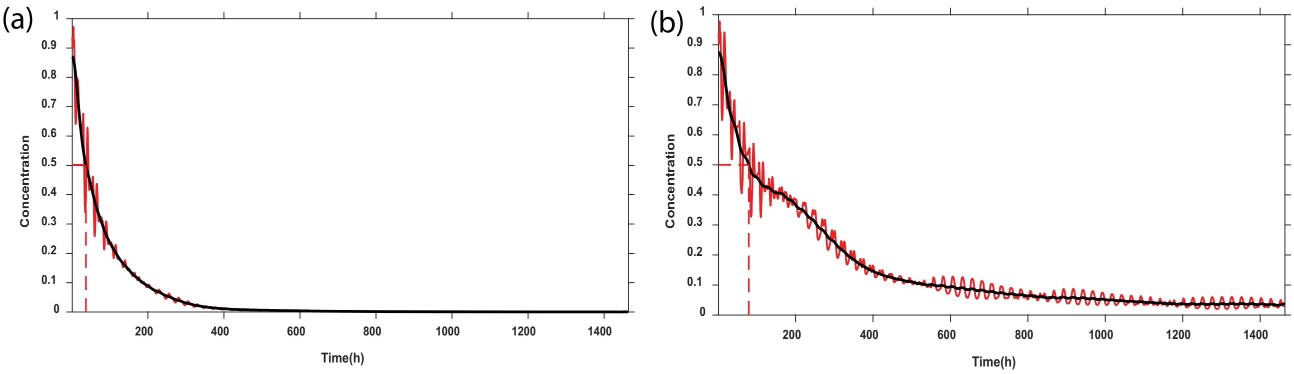

Fig. 7. Variation curve of the concentration of the conservative particle in the West Bay during the wet (a) and dry (b) periods.

under the joint action of tide, runoff and monsoon, the concentration of the conservative particles in the two bays decrease at a faster ratio. The concentration of the conservative particles in the estuary area of the West Bay decreases rapidly, and the decrease speed of the concentration is significantly faster than that in the East Bay. Because of the dynamic effect of astronomical tide, the average concentration in the two bays is bound to change periodically with the ebb and flow, and the semi-monthly periodic change also exists.

In this paper, the concentration of conservative particles in different periods during the wet and dry seasons is analyzed, and the results are presented in Figs. 8 and 9. It can be seen that the spatial distribution of the concentration in the East Bay increases from the entrance of the bay to interior, and the concentration in the main channel is significantly lower than that in the shallow water on both sides, which indicates that the capacity of water exchange in main channel is strong, and the reduction ratio of the concentration decreases with time. While the spatial distribution of the concentration in the West Bay increased from the estuary to the outside of the bay, and the concentration in the main channel of fresh water from Fangcheng River is significantly lower than that in the shallow water on both sides, which indicates the same that the capacity of water exchange in main channel is strong, and with the increase of time, the decrease ratio of the concentration decreases.

3.4. Water exchange time

According to the calculation, half-exchange period of sea water in the West and East bays is shown in Table 2. It is about 1.7 d in the wet season, and 3.6 d in the dry season in West Bay, while that is 15.2 d in the wet season and 27.8 d in the dry season in the East Bay. From the result of half-exchange period, it is significantly shorter in the wet season than that in the dry season. Runoff plays an accelerating role in pollutant's diffusion, and it is more effective than the monsoon.

4. Conclusion

The period of water exchange in Fangcheng Bay is mainly affected by the runoff from Fangcheng River and tidal current. The runoff of Fangcheng River is 99.85 m^3/s in the wet season and 33.28 m^3/s in the dry season, respectively. The numerical simulation shows that the maximum flow velocity in the West Bay can reach 1.0 m/s and that in the East Bay can reach 0.9 m/s.

Due to the existence of Fangcheng River, the spatial distribution of the concentration of conservative particles in the West Bay increased from the estuary to the outside of the Bay, and the concentration in the main channel of fresh water is significantly lower than that in the shallow water on both sides, which indicates that the capacity of water exchange in main channel is strong. While the spatial

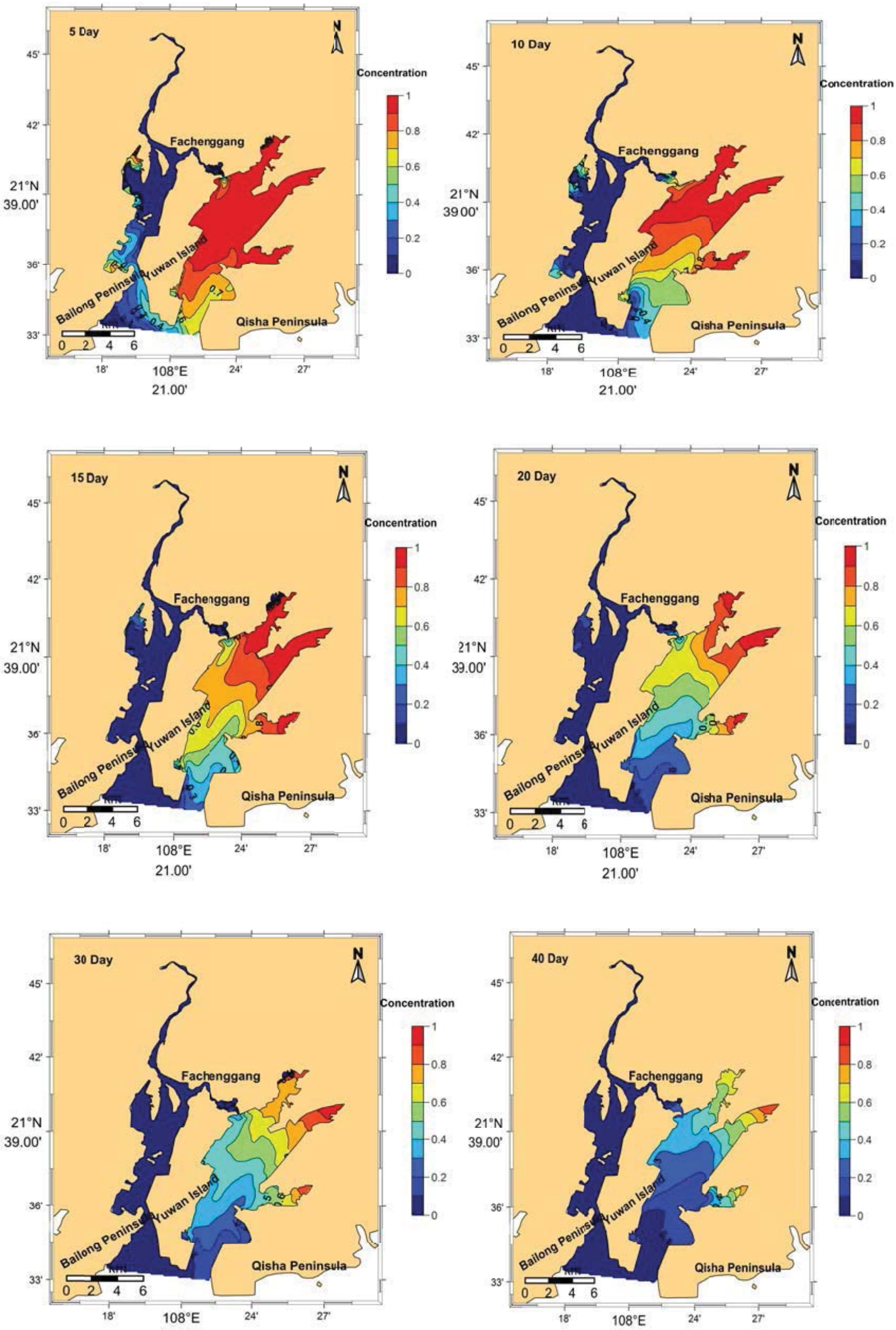

Fig. 8. Distribution of conservative particle concentration in Fangcheng Bay during the flood period.

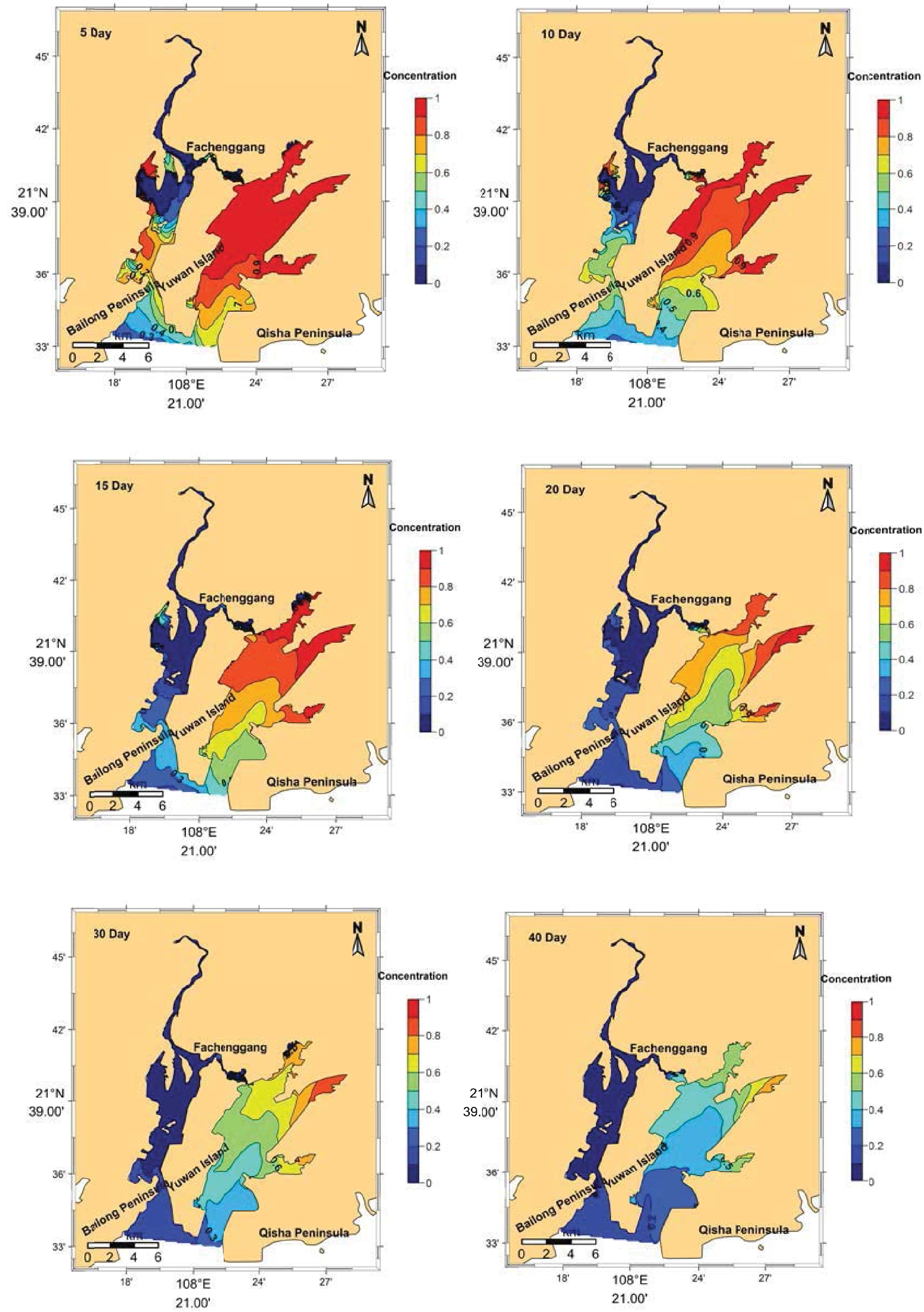

Fig. 9. Distribution of conservative particle concentration in Fangcheng Bay during the dry period.

Table 2
Water exchange situation of Fangcheng Bay

Research area	Area (km^2)	Half-exchange period (d)	
		Wet period	Dry period
West Bay	33.78	1.7	3.6
East Bay	60.27	15.2	27.8

distribution of the concentration in the East Bay increases from the entrance of the bay to interior, and the concentration in the main channel is significantly lower than that in the shallow water on both sides. The decrease ratio of the concentration in the two bays decreases with time.

Due to the larger tidal current velocity and the influence of runoff from Fangcheng River, the time of water exchange in West Bay is obviously shorter than that in East Bay, and the half-exchange period in West Bay is 1.7 d in wet season and 3.6 d in dry season. Because the East Bay is connected with the West Bay by a long narrow channel, the influence of runoff can be reflected obviously in wet season, and the half-exchange period is 15.2 d, while the effect is not obvious in the dry season with the half-exchange period of 27.8 d.

In conclusion, the capacity of water exchange in West Bay is better. In order to reduce environmental pollution and promote the sustainable development of the oceans and human health, the eastern shore of the central part of the West Bay with strong capacity of water exchange should be selected to set sewage pipes in future.

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