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Numerical study on the influences of Nanliu River runoff and tides on water age in Lianzhou Bay

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Abstract The concept of water age is applied to calculate the timescales of the transport processes of freshwater in Lianzhou Bay, using a model based on ECOMSED. In this study, water age is defined as the time that has elapsed since the water parcel enters the Nanliu River. The results show that the mean age at a specified position and the runoff of the Nanliu River are well correlated and can be approximately expressed by a natural logarithmic function. During the neap tide, it takes 70, 60 and 40 days in the dry, normal and rainy seasons for water to travel from the mouth of the Nanliu River to the northeast of Lianzhou Bay, respectively, which is not beneficial to water exchange in the bay. Tides significantly influence the model results; it takes five less days for the tracer to be transported from the mouth of the Nanliu River to the north of Guantouling during the spring tide than during the neap tide.

Keyword: Lianzhou Bay; passive tracer; numerical simulation; neap-spring variation; water age

1 INTRODUCTION

In estuarine and coastal areas, regional ecosystems are significantly influenced by incoming water, which carries carbon, nutrients, plankton, dissolved oxygen and suspended matter. For management and the ecosystem-related research, it is important to know the timescales of dissolved substances taken by the water body to transport from the source to any part of the system (Shen and Haas, 2004). Water age can be used to quantitatively describe this physical process, as is one of the measures in the study of water transport timescales. Moreover, since there is a time lag between river input and the associated concentration changes of particular dissolved substances (Sin et al., 1999), water age can also provide necessary information for analyzing monitoring data.

Since Bolin and Rhode (1973) introduced the concept of age, several methods have been adopted to calculate the age of a water parcel (Zimmerman, 1976; Takeoka, 1984). For example, a general age theory named Constituent oriented Age and Residence time Theory (CART) (Delhez et al., 1999; Deleersnijder et al., 2001; Delhez and Deleersnijder, 2002) has been developed and widely applied to study water renewal (Gourgue et al., 2007), mixing (Gustafsson and Bendtsen, 2007), vertical transport (White and Deleersnijder, 2007) and estuarine dynamics (Shen and Lin, 2006; Shen and Wang, 2007). In recent years, CART has also been applied in the China Sea area. For example, Wang et al. (2010), who applied the age concept to study the transport timescales and the change of estuarine circulation due to human activities in the Changjiang (Yangtze) River estuary. Shen et al. (2011) computed the average residence time and water age of the Dahuofang Reservoir. Liu et al. (2012) calculated the age of Huanghe (Yellow) River water in the Bohai Sea based on CART and a particle-tracking method. Wang et al. (2013) discussed the water transport characteristics in response to runoff in the Daliaohe Estuary in China.

Lianzhou Bay is a semi-circular bay with a 17-km-wide mouth. It is located near Beihai City in the northern of the Beibu Gulf (Fig.1). There are several rivers flowing into Lianzhou Bay, including the

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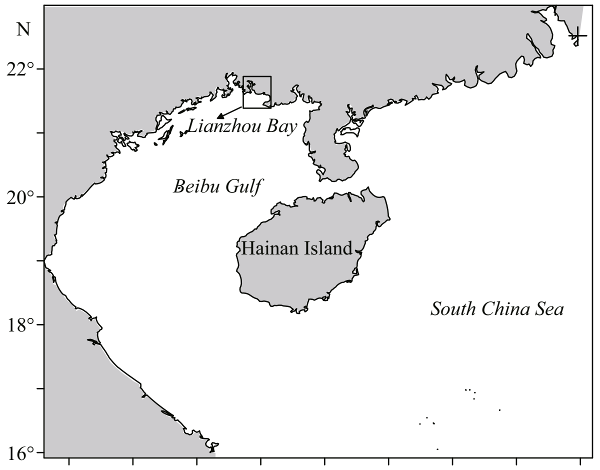


Fig.1 Location of the study area

Nanliu River, which is the largest river in the Guangxi Province. Previous studies have mainly focused on the concentration distribution of dissolved substances in Lianzhou Bay (Kaiser et al., 2013). Knowledge of the water age distribution and thus the residence time of substances in Lianzhou Bay are important for the water management and the understanding of the effect of Nanliu River on the deep tidal channel. In this study, the distribution characteristics of water age influenced by the Nanliu River runoff and tide in Lianzhou Bay are investigated based on the temporal and spatial variation of water age.

2 METHOD

2.1 Model description

The ECOMSED is a three-dimensional ocean model developed based on the Princeton Ocean Model (POM) and Estuaries, Coastal and Ocean Model (ECOM). It has been widely used in numerical simulations of coastal areas. In this model, the wetting and drying scheme was used to simulate the realistic flooding and drying processes for the inter-tidal zone in the Nanliu River estuary. A detailed description of the model and the governing equations can be found in Blumberg (2002).

There are several transport time scales to describe the characteristics of mass transport, including the residence time, the exposure time and water age. Residence time is the time taken by the water parcel to leave the control domain for the first time, exposure time is the total time spent by the water parcel in the control domain, and water age is the time elapsed since the water parcel leaves the source.

A general method for computing the age distribution based on numerical models is provided by CART. The age of water parcels can be calculated based on a tracer concentration and an age concentration, which can be obtained through Eqs.1 and 2, respectively:

$$\frac{\partial \boldsymbol{C}(\boldsymbol{t},\vec{\boldsymbol{x}})}{\partial \boldsymbol{t}} = -\nabla\left[\boldsymbol{u}C(\boldsymbol{t},\vec{\boldsymbol{x}}) - \boldsymbol{K}\nabla \boldsymbol{C}(\boldsymbol{t},\vec{\boldsymbol{x}})\right], \tag{1}$$

$$\frac{\partial \alpha(\boldsymbol{t},\vec{\boldsymbol{x}})}{\partial \boldsymbol{t}} = \boldsymbol{C} - \nabla\left[\boldsymbol{u}\alpha(\boldsymbol{t},\vec{\boldsymbol{x}}) - \boldsymbol{K}\nabla \alpha(\boldsymbol{t},\vec{\boldsymbol{x}})\right], \tag{2}$$

where C is the tracer concentration, α is the age concentration, u is the velocity vector, $\boldsymbol{K}$ is the diffusivity tensor, t is the time, and $\vec{\boldsymbol{x}}$ is the position vector.

The mean age a can be calculated as follows:

$$\boldsymbol{a}(\boldsymbol{t},\vec{\boldsymbol{x}}) = \frac{\alpha(\boldsymbol{t},\vec{\boldsymbol{x}})}{\boldsymbol{C}(\boldsymbol{t},\vec{\boldsymbol{x}})}. \tag{3}$$

Each water parcel is treated as a passive tracer. Equations 1–3 were used to compute the age of water parcels using the tracer module in ECOMSED, with specified initial and boundary conditions.

2.2 Model setup

The model grid contained 11, 220 rectangle elements, with a mesh spacing of 350 m. The bottom drag coefficient was set to 0.002 5. The bottom roughness height was set to 0.002 m. The Smagorinsky eddy parameterization method was applied to calculate the horizontal diffusion (Smagorinsky, 1963) (Eq.4). In this formula, the value of C in the range, 0.10 to 1.0 seem to work well. In this paper, the value is 3. The vertical mixing coefficients were obtained through a second order turbulence closure scheme (Mellor and Yamada, 1982). The bathymetry was from the China Nautical Charts (16 710 and 16 771), while parts of the river channel and inter-tidal zone come from observational data. The map of the area used in the model, with the depths, is shown in Fig.2.

$$\nu = \boldsymbol{C}\Delta \boldsymbol{x}\Delta \boldsymbol{y}[(\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{x}})^2 + \frac{1}{2}(\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{y}} + \frac{\partial \boldsymbol{v}}{\partial \boldsymbol{x}})^2 + (\frac{\partial \boldsymbol{v}}{\partial \boldsymbol{y}})^2]^{\frac{1}{2}}. \tag{4}$$

According to observational data, 72 m^3/s, 132 m^3/s and 350 m^3/s were selected to represent the river runoff conditions in the Nanliu River during dry, normal, and rainy seasons, respectively. In addition, the runoff of the Dafeng River was set as a constant (83 m^3/s). Four tidal constituents (K_1, O_1, M_2, and S_2) were used to specify the tidal open boundary for the model.

The total simulation time in the model was 300 days. The model initially ran for 20 days for each runoff condition to obtain a dynamic equilibrium condition. Then, the tracer was continuously released at the Nanliu River, with a concentration of 1 (arbitrary units). After 200 days, the model reached equilibrium.

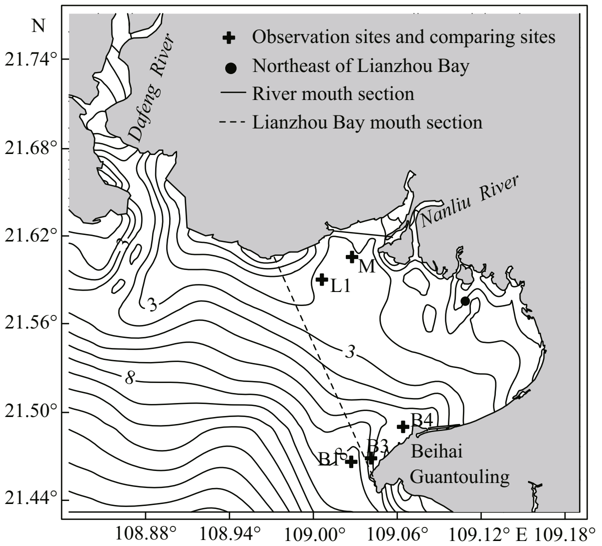


Fig.2 Map of Lianzhou Bay

B1, B3, B4 are observation sites.

3 RESULT

3.1 Model validation

Water levels from in-situ data at stations B1, B3 and B4 were used for model validation. As shown in Fig.3, the simulated water level at the three stations agreed well with the observational data, which indicated that a relatively accurate hydrodynamic field could be provided for the calculation of water age. Figure 4 shows the distribution of surface currents at the moment of maximum ebb and maximum flood. It can be seen that the ebb current direction in Lianzhou Bay is mainly from northeast to southwest, while part of the current flows out of the bay along Guantouling and then turns towards the southeast. The maximum ebb flow velocity is about

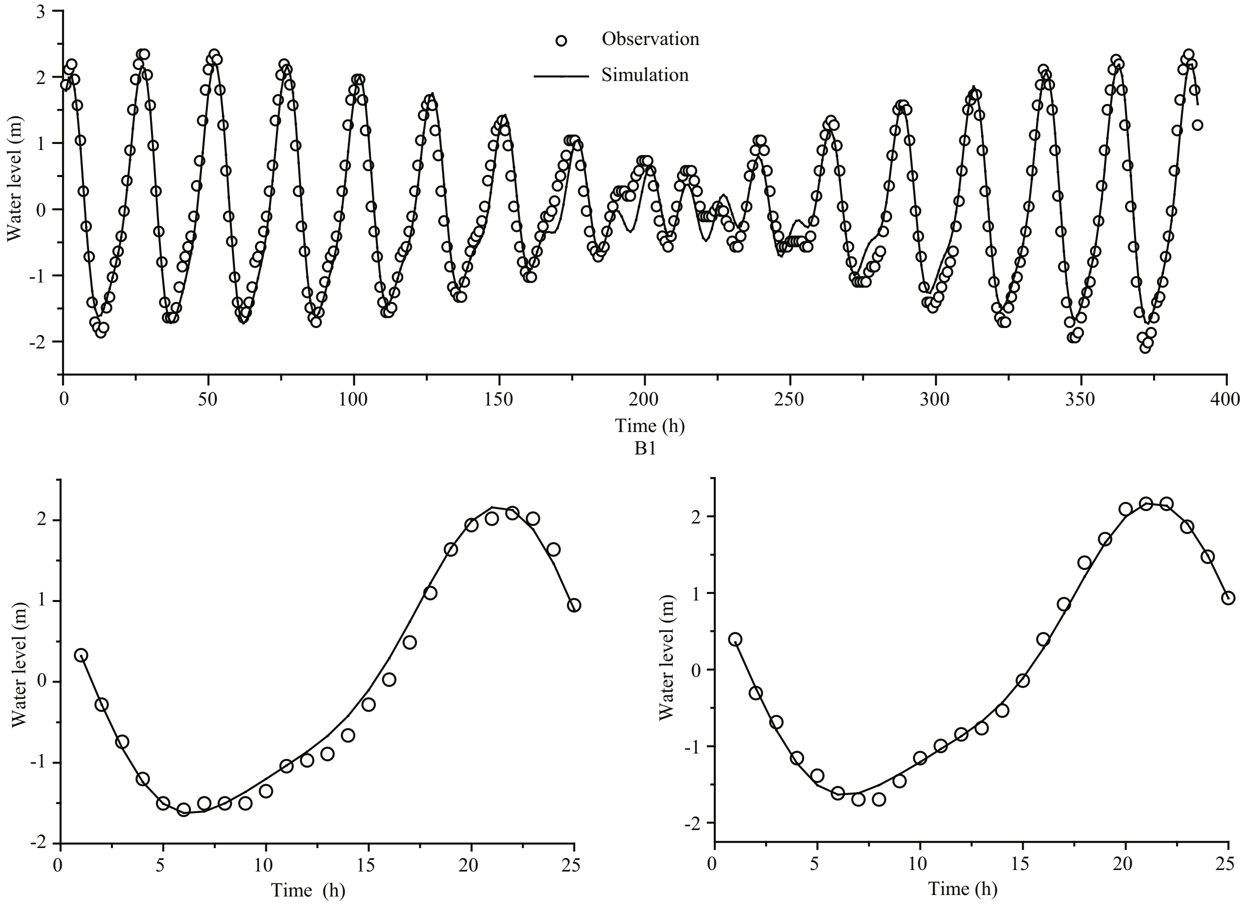
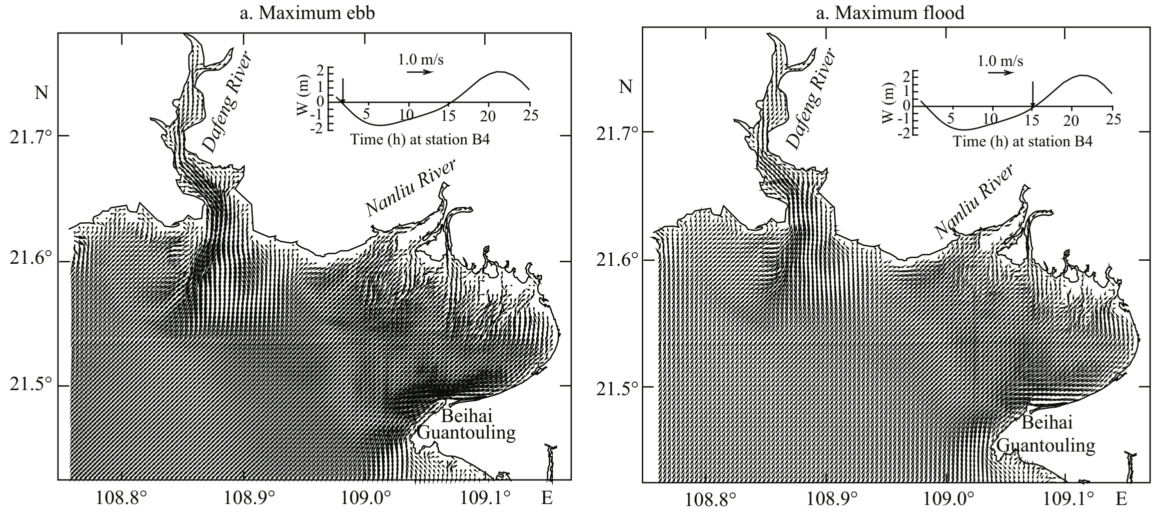


Fig.3 Comparison of simulated and observed water levels at station B1, B3 and B4


a. Maximum ebb

a. Maximum flood

Fig.4 Simulated surface currents

58 cm/s. The direction of the flood current in Lianzhou Bay is mainly from southwest to northeast. The flow velocity of the maximum flood tide reaches 36 cm/s, indicating that the ebb flow is much larger than the flood flow.

3.2 The influence of runoff on age distribution

3.2.1 Horizontal distribution characteristics

Since the water in Lianzhou Bay is very shallow, the age was averaged vertically for analysis. Figure 5 shows the contour maps of the tidally driven average age distribution during neap and spring tides in the dry, normal, and rainy seasons.

Runoff had a significant influence on age distribution. It took approximately 70, 60 and 45 days for tracers to be transported from the mouth of the Nanliu River to Guantouling, respectively, which shows that the transportation of the tracer increases in speed as river flow increases. Overall, there is a westward spread of younger water in Lianzhou Bay due to the anticlockwise rotation of the local tidal wave system. During a neap tide, it takes 70, 60 and 40 days for water to travel from the river mouth to the northeast of Lianzhou Bay, while only 15, 10 and 5 days are needed, respectively, to move water westwards out of Lianzhou Bay. These differences in horizontal distribution of water age have a negative effect on the water exchange.

3.2.2 The correlation between age and runoff

Age distribution at a specific location is a function of total freshwater discharge (Shen and Haas, 2004; Wang et al., 2013). Six runoff conditions were chosen to examine the relationship between age and runoff in the Nanliu River. Figure 6 shows the results of regression analysis of mean age versus runoff. The relationship between the mean age (a) at three stations (M, L1 and B1) and runoff (Q) could be described as a natural logarithmic function (Eq.5), where m and n are positive constant as follows:

$$a=-m\ln(Q)+n. \tag{5}$$

The formula shows that as runoff increases, the mean age at certain locations will decrease. The coefficients of the correlation, R_2, for these locations were greater than 0.99, which indicates high reliability of this regression analysis.

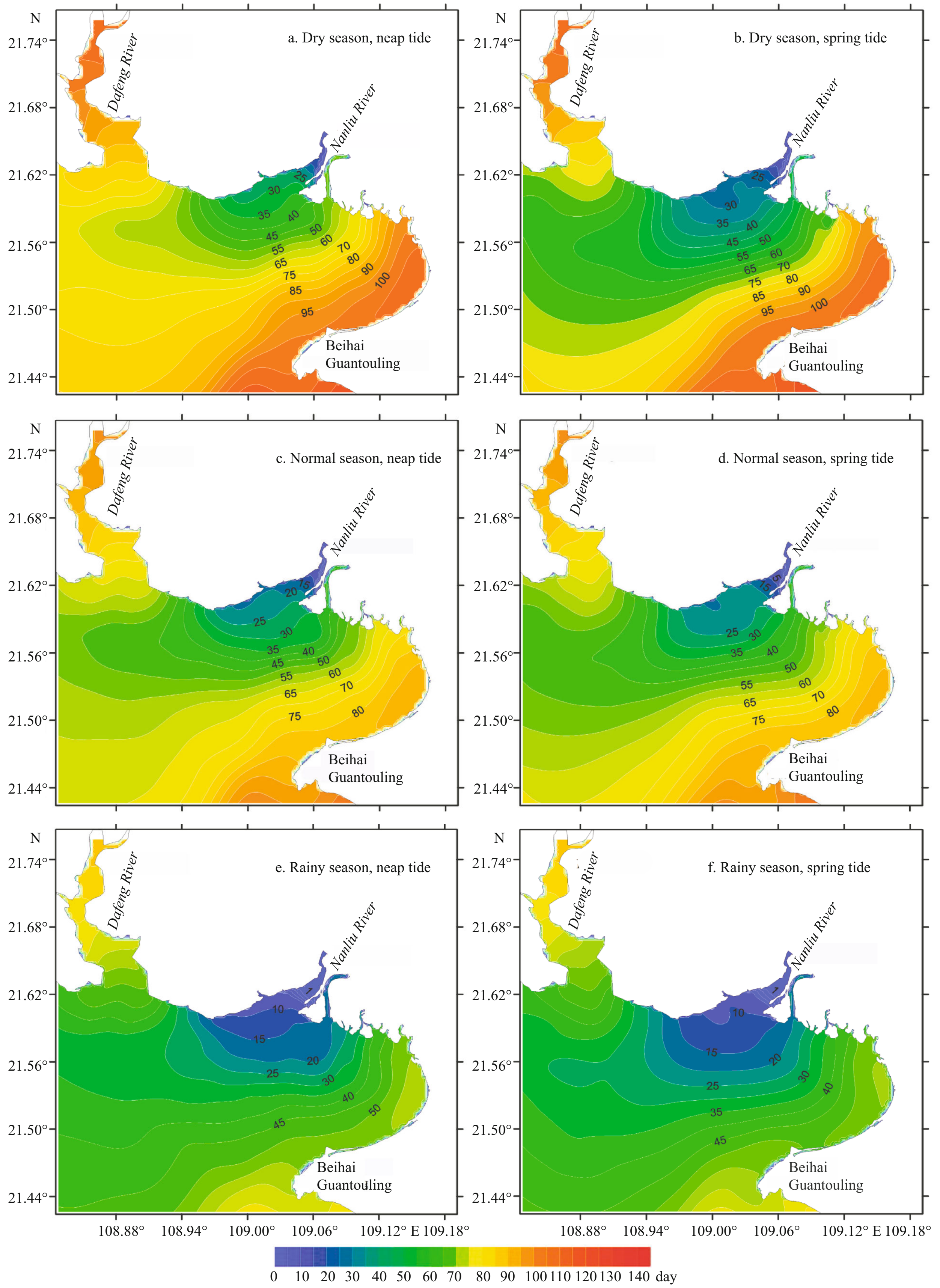
3.3 The influence of tides on age distribution

3.3.1 Horizontal distribution characteristics

Spring and neap tides have different influences on the horizontal distribution of water age in Lianzhou Bay. During the spring tide, there is a significant jacking force by the tidal current, while the interaction between runoff and the tides is strong, resulting in a more widespread distribution of the tracer than during the neap tide (Fig.5).Thus, during the spring tide, the water age becomes less than during the neap tide. For example, during the spring tide it takes 5 less days than during the neap tide for the tracer to be transported from the river mouth to the north of Guantouling, where the tidal current enters into Lianzhou Bay.

3.3.2 The relationship of age distribution with tides

The time series of age and water level in the last 45 days at station M during the normal season were output to examine the age distribution characteristics at a specific location as shown in Fig.7. In a constant


a. Dry season, neap tide

b. Dry season, spring tide

c. Normal season, neap tide

d. Normal season, spring tide

e. Rainy season, neap tide

f. Rainy season, spring tide

Fig.5 The vertically averaged water age distributions (in days) during the neap and spring tides in the dry, normal, and rainy season

runoff condition, the age actually oscillates at a period of about 14 days, which is consistent with the period of the neap-spring tide cycle. The correlation coefficients of age against water level at station B1, L1, and M are 0.791 0, 0.599 7 and 0.185 2, respectively ($P<0.05$), which indicates that the greater the distance from the Nanliu River to the site, the greater the influence of tide on water age.

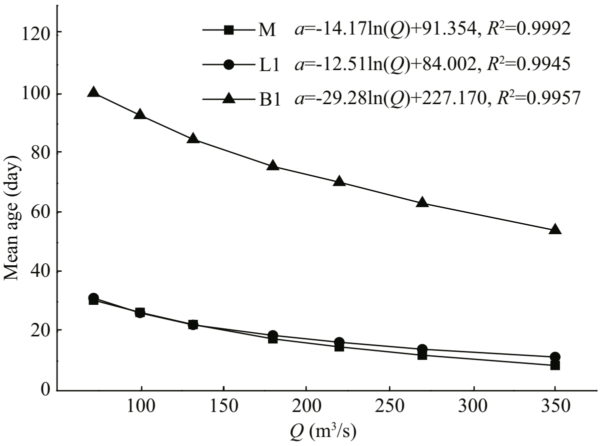


Fig.6 Age distributions with respect to runoff at selected stations

As shown in Fig.8, during the spring tide, water age oscillates regularly with water level. The water age has an increasing trend during the neap tide instead of periodic oscillations during the spring tide. The neap-spring tide variation also plays an important role in the variation of age at other locations.

4 DISCUSSION

Beside of the tide and the river runoff, the diffusion coefficient and wind have an effect on the result of the water age. Generally, in the Smagorinsky formula (Eq.4), the values C is in the range of 0.10 to 1.0. To study the sensitivity to the coefficient, we set the coefficient C as 1.0, 0.8, 0.5, 0.3, 0.2, respectively, and the runoff is in the normal season.

We choose the B1, B3 and B4 stations (Fig.2) to see the changes of the tests. The water age turn to larger with the decrease of the coefficient. The cause is that the mass transfer speed will become slowdown

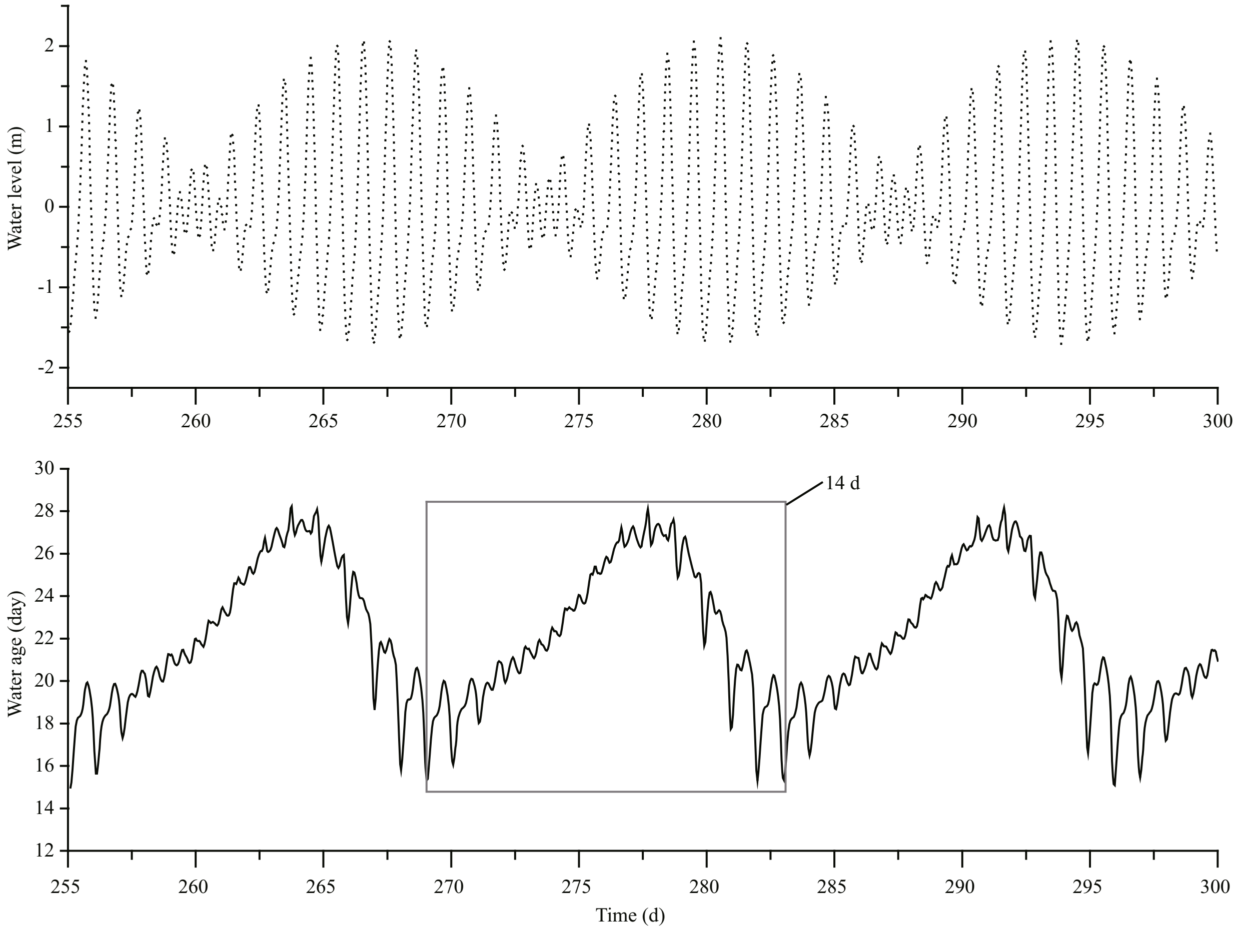


Fig.7 Time series of water age at station M during the normal season

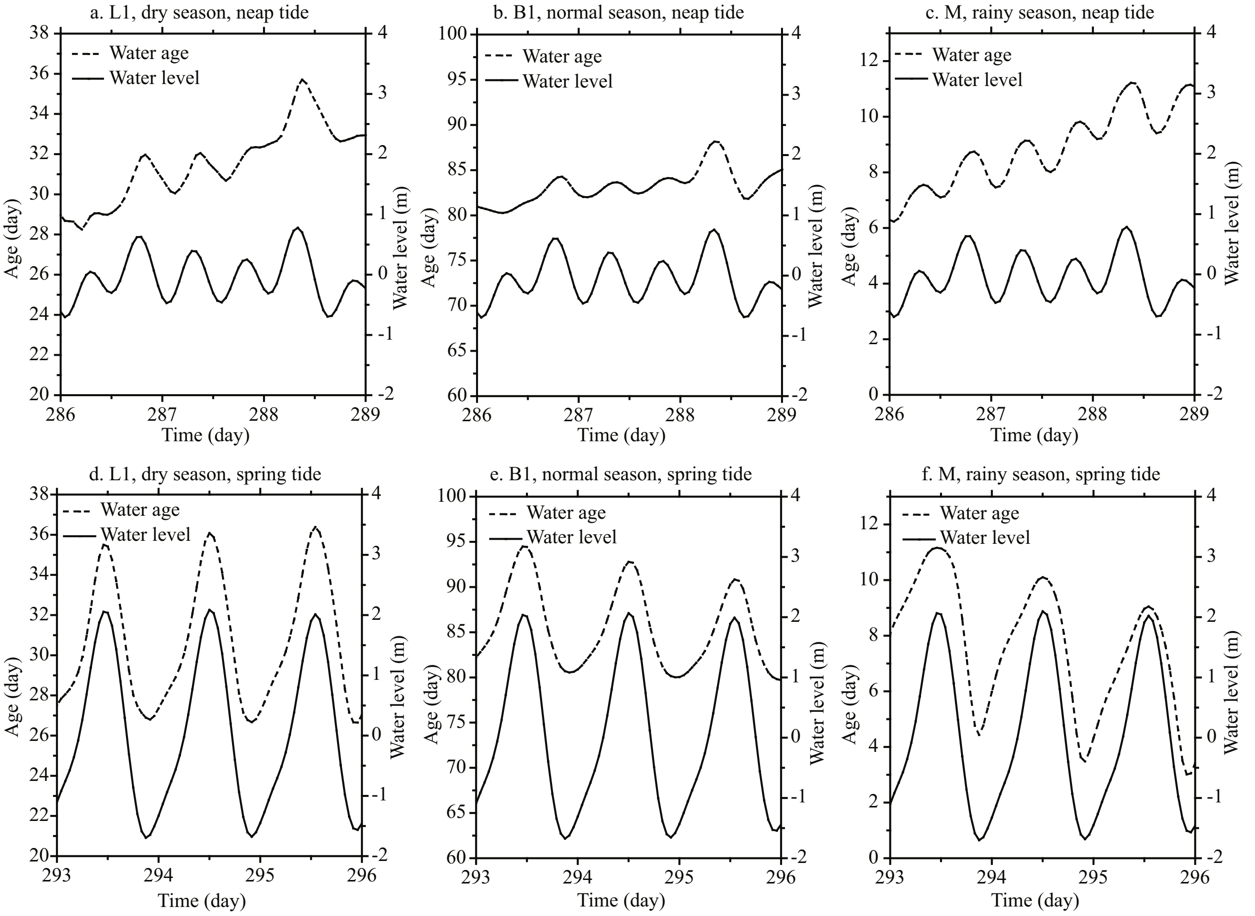


Fig.8 Time series of water age for the special locations in different runoff and tidal conditions

with the decrease of the coefficient. The experimental results show that the coefficient has something to do with the water age. The difference of the result is about 20d at the B1 station, but it is little in B3 and B4.

In the study area, the prevailing wind direction is north, and the average wind speed is about 2.8 m/s. We compared the results between no wind condition and north wind condition. With considering the north wind, the water ages are 17 d, 27 d and 65 d, respectively. In contrast, under windless condition, the water ages are 25 d, 37 d and 89 d, respectively. Thus the wind has noticeable effect on the water age.

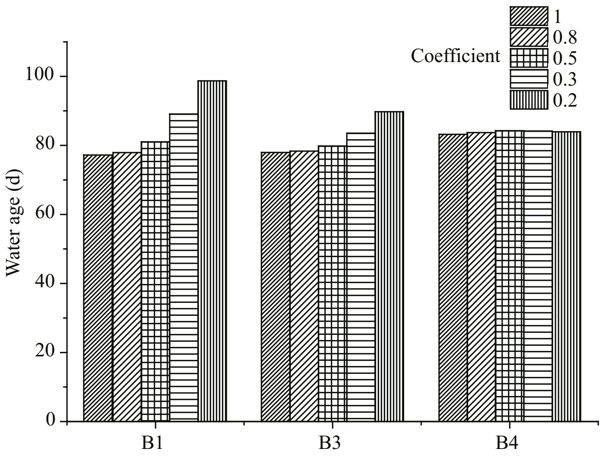


Fig.9 Coefficient effect on water age at M, L1, B1

5 CONCLUSION

The water age based on CART was calculated to investigate the water transport processes influenced by runoff and the tides in Lianzhou Bay. The results of this paper show that the age distribution varies in response to changes in runoff and the tides. Runoff had a significant influence on the horizontal age distribution in Lianzhou Bay: it takes about 70, 60 and 45 days for tracers to be transported from the mouth of the Nanliu River to Guantouling during the dry, normal and rainy seasons, respectively. The westward trend of age distribution in Lianzhou Bay had a negative effect on water exchange in the northeast of the bay. The relationship between the average age for a specified location and runoff could be expressed approximately by a natural logarithmic function. The interaction between the tides and runoff is strong in the spring tide, which leads to a significant age difference. During the spring tide, it took five less days when compared to the neap tide, for the tracer to be transported from the mouth of the Nanliu River to the north of Guantouling. In addition, the wind and the diffusion coefficient have noticeable effect on the water age.

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