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Numerical Modeling Tidal Circulation and Morphodynamics in a Dumbbell-Shaped Coastal Embayment

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1. Introduction

Channel-shoal (ridge) system is a common morphological feature in wide, shallow coastal bays and estuarine mouth where tidal flow is relatively stronger. Sediment transport and morphological evolution is complex within such a system as constrained by interacting tidal force, river current, sediment source and characteristics, shoreline configuration, etc.

As the deeper tidal channels are usually utilized as navigation courses or water supply source for coal & nuclear power plants or other engineering purposes, it is vitally important to maintain the stability of these tidal channels, that is, they should not be allowed to migrate, merge or perish by siltation.

This chapter chooses the dumbbell-shaped Qinzhou Bay as the study site to investigate the sediment transport process and resultant morphological evolution of the channel-shoal system within the Bay using numerical simulations under the status quo situation. This is beneficial to the planned large-scale coastal engineering projects that might exert a profound long-term influence upon the stability of the channel-shoal system.

1.1. Research question

Qinzhou Harbor is one of the most important sea harbors connecting southwestern China's inland and the southeast Asian countries, it delivered up to 47.162 million ton cargos in 2011. The harbor has been using waterways as its navigational channel. Meanwhile, coal & nuclear power plants, industrial development zones, recreational parks, land reclamations and many other coastal projects have been or planned to be constructed around the Qinzhou Bay coast, all of which compete for the limited shoreline and water area resources.



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For the optimum planning of the coastal engineering projects regarding size, location and the sustainable regional economic, social and environmental development, it is critically urgent to know how the stability of the channel-shoal system under the present coastal configuration and bathymetry. This might be answered by investigating the sediment transport processes and morphodynamics of the channel-shoal system.

1.2. Site description

Qinzhou Bay is located on Guangxi Province's coast facing South China Sea (Figure 1).



Figure 1. Sketch map of Qinzhou Bay coastal configuration (the axis is local coordinate, unit: m).

Appearing as a dumbbell shape it consists of three parts: the inner enclosed bay, also known as Maoweihai, the outer bay and the Yingling tidal inlet connecting two bays. Two rivers, i.e. Maolingjiang and Qinjiang flow into the inner bay, delivering annually 27.73×10⁹ m³ water and 86.4×10³ t sediment; the outer bay is a show, trumpet-shaped bay, its area is nearly 2.55×10⁸ m² with a mean depth of 4.67m (calculated by mean sea level). A complex channel-shoal system is present within the outer bay, consisting of three dominant tidal waterways, i.e. the east waterway, middle waterway and west waterway and

sand ridges/shoals between them (Figure 1). The Yingling tidal inlet is 10.1 km long and 1.1~3.5 km wide with a water depth of 5~20 m; it is a rocky inlet with a total of 71 various-sized islands and 72 narrow, small waterways.

2. Dynamics

2.1. Tidal regime

The spring tide and middle tide in Qinzhou Bay are diurnal throughout most of the year but become irregularly diurnal in March and September each year, while the neap tide is usually semi-diurnal throughout the whole year. The mean tidal range is 2.51m, and the maximum tidal range is 5.27m. The flood tides last longer than the ebb tides in spring, middle and neap tides. It is 13 hours plus 14 minutes, 11 hours plus 18 minutes for spring tide; 14 hours plus 36 minutes and 10 hours plus 7 minutes for middle tide, and 6 hours plus 33 minutes and 5 hours plus 40 minutes for neap tide, respectively [1].

Tidal flow in the outer bay demonstrates as reciprocating flow in parallel to the major waterways; the mean flood velocity, ebb velocity of spring tide is 0.37m/s and 0.51 m/s, respectively, the mean flood velocity, ebb velocity of middle tide is 0.33m/s and 0.38 m/s, respectively, the mean flood velocity, ebb velocity of neap tide is 0.22m/s and 0.18 m/s; while flow velocity in the Yingling inlet becomes significantly larger, the mean flood velocity, ebb velocity of spring tide is 0.67m/s and 0.90 m/s, the mean flood velocity, ebb velocity of middle tide is 0.57m/s and 0.68 m/s, the mean flood velocity, ebb velocity of neap tide is 0.42m/s and 0.33m/s, respectively, and the maximum flood flow velocity reaches up to 1.40 m/s and the maximum ebb flow velocity is up to 1.32 m/s [1].

2.2. Wave climate

The Qinzhou Bay is influenced by subtropical monsoon and the waves within the Bay are mainly wind-driven with some surge waves traveled from the open sea.

The waves in winter season (October~Apirl) prevail in N-NE direction while they prevail in S-SW direction in summer season (May-September) and the stronger waves propagate in SSW, SSE directions; the mean wave height is 0.52m and mean wave period is 3.1s [2].

3. Sediment characteristics

3.1. Suspended sediment

Suspended sediment concentration within Qinzhou Bay water is generally low. In summer 2009, the mean full tidal concentration is 0.022 kg/m³, among which, it is 0.035 kg/m³ in spring tide, 0.020 kg/m³ in middle tide and 0.013 kg/m³ in neap tide; the maximum concentration is 0.081 kg/m³, occurred in spring ebb tide, the maximum middle tidal concentration

is 0.034 kg/m³, occurred also in ebb tidal period, the maximum neap tidal concentration is 0.025 kg/m³, occurred also in ebb tidal period [1].

The medium diameters of suspended sediment vary within 0.0067~0.0152mm with a mean value of 0.0101mm. The suspended sediment is mainly clayey silt with 30.8% clay particles, 53.4% silt particles and 15.8% sand particles (Table 1). The sorting index is 1.90 [1].

Grading sand sint clay sorting index	Cuadina	and a		alax.	Continu index
	Grading	Sanu	SIL	Clay	Sorting index

Table 1. Grading of suspended sediment.

3.2. Bottom sediment

The bottom sediments in Qinzhou Bay mainly consist of gravel, coarse sand, medium sand, fine sand, silty clay and clayey silt, etc.



Figure 2. Bottom sediment grain size distribution in Qinzhou Bay.

The gain sizes vary remarkably in $0.0027 \sim 1.099$ mm (Figure 2). The spatial mean median diameter (D₅₀) in the inner bay is 0.334mm; it is 0.356mm in the deep channel but becomes 0.0041mm in the shallow parts in the Yingling inlet; in the outer bay, the spatial mean D₅₀ is about 0.298mm with an overall deposition pattern: coarser in waterways but finer in shoals, and coarser in the western part than in the eastern part of the bay [1].

3.3. Sediment source

The Qinzhou Bay has been a drowned rocky valley by the last sea level transgression since 7,000-8,000 year before present [3]. Therefore, the huge amount of sand deposits in the outer bay has come from the deposits by paleo-Maolingjiang river and paleo-Qinjiang river, they have been reformed into the contemporary channel-shoal geomorphology by tidal dynamics. At the present day, sediments delivered by these two rivers are deposited within the inner bay with limited amount of fine particles transported into the outer bay and open sea; meanwhile, limited amount of sediment eroded from the adjacent slopes by storm rains also enter the outer bay. Generally speaking, sediment from the open sea into the Qinzhou Bay is very limited.

4. Numerical model

A 3D unstructured grid, finite-volume coastal ocean model (called FVCOM) has been developed in the Marine Ecosystem Dynamics Modeling Laboratory led by Dr. C. Chen at the University of Massachusetts–Dartmouth (UMASS-D) in collaboration with Dr. R. Beardsley at the Woods Hole Oceanographic Institute. FVCOM is a three-dimensional (3D) primitive equation ocean model, consisting of momentum, continuity, sediment, temperature, salinity, and density equations and is closed physically and mathematically using the Mellor and Yamada level-2.5 turbulent closure submodel; the irregular bottom slope is represented using a σ -coordinate transformation, and the horizontal grids comprise unstructured triangular cells; the finite-volume method used in the model combines the advantages of a finite-element method for geometric flexibility and a finite-difference method for simple discrete computation; current, sediment, temperature, and salinity in the model are computed in the integral form of the equations, which provides a better representation of the conservative laws for mass, momentum, and heat in the coastal region with complex geometry [4].

4.1. The primitive equations

The governing equations consist of the following momentum, continuity, temperature, salinity, and density equations:

(1) continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

(2) *x*-direction momentum equation

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_0} \frac{\partial P}{\partial x} + \frac{\partial}{\partial z} \left(K_m \frac{\partial u}{\partial z} \right) + F_u$$
(2)

(3) *y*-direction momentum equation

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_0} \frac{\partial P}{\partial y} + \frac{\partial}{\partial z} (K_m \frac{\partial v}{\partial z}) + F_v$$
(3)

(4) temperature equation

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = \frac{\partial}{\partial z} \left(K_h \frac{\partial T}{\partial z} \right) + F_T$$
(4)

(5) salinity equation

$$\frac{\partial s}{\partial t} + u \frac{\partial s}{\partial x} + v \frac{\partial s}{\partial y} + w \frac{\partial s}{\partial z} = \frac{\partial}{\partial z} \left(K_h \frac{\partial s}{\partial z} \right) + F_s$$
(5)

(6) pressure equation

$$\frac{\partial P}{\partial t} = -\rho g \tag{6}$$

$$\rho = \rho(T, s) \tag{7}$$

where *x*, *y*, and *z* are the east, north, and vertical axis of the Cartesian coordinate; *u*, v, and *w* are the *x*, *y*, *z* velocity components; *T* is the potential temperature; *s* is the salinity; *P* is the pressure; *f* is the Coriolis parameter; *g* is the gravitational acceleration; K_m is the vertical eddy viscosity coefficient; and K_h is the thermal vertical eddy diffusion coefficient. Here F_u , F_y , F_T , and F_s represent the horizontal momentum, thermal, and salt diffusion terms.

4.2. Numerical solutions

The momentum and continuity equations are solved using a 'model splitting' method [4], that is, the current is divided into external and internal modes that can be computed using two distinct time steps. The external mode is used to solve the 2D vertically integrated momentum and continuity equations while the internal mode is computed for the 3D equa-

tions, the latter is solved numerically using a simple combined explicit and implicit scheme, in which the local change of the current is integrated using the first-order accuracy upwind scheme; the advection terms are computed explicitly by a second-order accuracy Runge–Kutta time-stepping scheme [4].

4.3. Sediment computation

FVCOM adopts the Community Numerical Modeling System to simulate erosion, transport, deposition and the fate of sediments in the coastal ocean developed by experts from USGS [5]. The sediment-transport algorithms are implemented for an unlimited number of user-defined noncohesive/cohesive sediment classes. Each class has attributes of grain diameter, density, settling velocity, critical stress threshold for erosion, and erodibility constant. These properties are used to determine bulk properties of each bed layer. Suspended-sediment transport in the water column is computed with the same advection-diffusion algorithm used for all passive tracers and an additional algorithm for vertical settling that is not limited by the CFL criterion [5].

4.3.1. Suspended sediment

Suspended sediment transport equation is:

$$\frac{\partial C_i}{\partial t} + \frac{\partial u C_i}{\partial x} + \frac{\partial v C_i}{\partial y} + \frac{\partial (\omega - \omega_i) C_i}{\partial z} = \frac{\partial}{\partial x} (A_{s,h} \frac{\partial C_i}{\partial x}) + \frac{\partial}{\partial y} (A_{s,h} \frac{\partial C_i}{\partial y}) + \frac{\partial}{\partial z} (K_{s,h} \frac{\partial C_i}{\partial z})$$
(8)

here C_i is the concentration of the *i*th sediment class, $A_{s,h}$ is the horizontal sediment diffusivity, $K_{s,h}$ is the vertical sediment diffusivity, ω_i is the settling velocity of the *i*th sediment class given by the user.

At the top boundary, the vertical diffusive flux is set to be zero:



here ζ is surface elevation. At the bottom boundary, the vertical sediment flux is specified by:

$$K_{s,h}\frac{\partial C_i}{\partial t} = E_i - D_i, z = -D \tag{10}$$

here *D* is water depth. While the erosion flux of the *i*th sediment class is computed as:

$$E_{i} = \Delta t E_{0i} (1 - P_{b}) F_{bi} (\frac{\tau_{b}}{\tau_{ci}} - 1)$$
(11)

where E_{0i} is an empirical constant set by the user as the erosion rate of the *i*th sediment class, P_b is the porosity of the bed, F_{bi} is the fraction of the *i*th sediment class, τ_b is the bottom flow shear stress, τ_{ci} is the critical stress for the incipient motion of the *i*th sediment class.

When the bottom shear stress passes the critical stress erosion occurs on the bed. The sediment concentration profile in the water body is determined by horizontal convection, diffusion, vertical diffusion, settling and bottom erosion flux [5].

4.3.2. Bedload transport computation

Bedload transport rate is computed using established empirical formula, i.e. the Meyer-Peter and Muller formula or using formulas that the modeler considers appropriate, for example, the theoretical-based formula [6].

4.3.3. Sediment bed

The sediment bed consists of a constant number layers, and each layer is initialized with a thickness, sediment-class distribution, porosity, and age, the mass of each sediment class can be determined from these values and the grain density; the bed evolving properties include bulk properties of the surface layer (active-layer thickness, mean grain diameter, mean density, mean settling velocity, mean critical stress for erosion) [5].



Figure 3. Distribution of vertical layers in bed model (from [5]).

The bed layers are modified at each time step to account for erosion and deposition (Figure 3) and track stratigraphy; at the beginning of each time step, an active-layer thickness z_a is calculated based on the relation of Harris and Wiberg [7]:

$$z_{a} = \max\left[k_{1}(\tau_{sf} - \overline{\tau_{ce}})\rho_{0}, 0\right] + k_{2}D_{50}$$
(12)

where τ_{sf} is bottom skin-friction stress; $\overline{\tau_{ce}}$ is the critical stress for erosion; and the overbar indicates this is averaged over all sediment classes; D₅₀ is the median grain diameter of surface sediment; and k_1 and k_2 are empirical constants, 0.007 and 6.0, respectively.

Each sediment class can be transported by suspended-load and/or bedload; suspended-load mass is exchanged vertically between the water column and the top bed layer; mass of each sediment class available for transport is limited to the mass available in the active layer; bedload mass is exchanged horizontally between the top layers of the bed; mass of each sediment class available for transport is limited to the mass available in the top layer [5].

If continuous deposition results in a top layer thicker than a user-defined threshold, a new layer is provided to begin accumulation of depositing mass; the bottom two layers are then combined to conserve the number of layers; after erosion and deposition have been calculated, the active-layer thickness is recalculated and bed layers are readjusted to accommodate it [5].

5. Model setup

5.1. Model domain

Figure 4 shows the computation domain consisting of unstructured triangular grids.



Figure 4. Unstructured grids of Qinzhou Bay.

It has 16466 nodes and 29722 elements in each horizontal layer and 7 sigma-levels in the vertical. The horizontal grid resolution varies from 2,000 m at the open boundary to 350m in the channel-shoal region to 150 m in the Yingling inlet, especially, down-to-30-m elements are interpolated around islands and in the estuarine channels.

5.2. Boundary conditions

The open boundary uses observed water level as input condition, for this purpose halfmonth water levels at each open boundary grid are interpolated from two tidal station, i.e. the Beihai Station and the Bailongwei Station (Figure 4). River boundaries use annuallymean discharges as input conditions.

Suspended-sediment concentrations at the open boundary grids are interpolated from adjacent observation sites, while those at river input grids are annually-mean suspendedsediment discharges.

The bathymetry in the computation domain consists of a local bathymetric survey in the Qinzhou Bay in 2008 and sea maps surveys in 2004 and 1997 to supplement other parts.

The time step for both of external mode and internal mode is 1 s.

6. Calibrations

TCZC [1] measured half month water level at three temporary tidal gauges, namely, Guozishan, Shabadun and Wulei, also measured 26-hour spring, middle and neap tidal flow velocity & direction and suspended-sediment concentrations at 10 sites (Figure 5).



Figure 5. Tidal gauges (red square) and flow observations sites (green triangular) in Qinzhou Bay.

The present study firstly performs the calibrations of water level, flow velocity& direction and suspended-sediment concentrations.

6.1. Tidal water level

The Calibrations for water levels at three tidal gauges are shown in Figure 6.





Figure 6. Tidal water level calibrations (the ordinate unit of is meter).

6.2. Flow calibrations

2

The flow calibrations are shown in Figure 7. For limited space only calibrations for spring tide are show here.





Figure 7. Flow calibrations.

6.3. Sediment calibration

Sediment calibrations for selected sites are shown on Figure 8. It needs to explain that the overall sediment calibrations are satisfactory, but results for some sites are not satisfactory enough due to observation and computation errors, ship activities and dredging during the observation period, etc.

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Figure 8. Suspended-sediment calibrations at selected sites for spring tide (the ordinate unit is kg/m³).

6.4. Morphological calibration

Based upon a local bathymetric survey conducted in 2008 summer and a sea map surveyed in 2004, statistics shows that the total siltation amount at this area is about 1.52 million m³ with a spatial average value of 0.592m (the deposition volume is divided by the deposition area, the same hereinafter), the total erosion amount is nearly 3.35 million m³ with a spatial average value of 1.104m (the erosion volume is divided by the erosion area, the same hereinafter), the net eroded sediment amounts to 1.83 million m³ (Figure 9).



Figure 9. Erosion & deposition distribution map in a part of Qinzhou Bay.

The present study computes the morphological evolution using the 2004 bathymetry as the initial bathymetry, the computed four-year accumulative erosion & siltation distribution is shown in Figure 10. The computed total siltation amount is 1.244 million m³ with a spatial average value of 0.461m, amounting 81.89% and 77.87% of surveyed quantities, respectively; the computed total erosion amount is 2.97 million m³ with a spatial average value of 1.073m, amounting 88.53% and 97.19% of surveyed quantities, respectively; the computed net eroded sediment amounts to 1.72 million m³, amounting 94.03% of surveyed quantities.

In view of the discrepancies of computed results vs. surveyed quantities the present morphological calibration is quite satisfactory. This lays down very good basis for further morphodynamic study.

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Figure 10. The computed 2004~2008 erosion & deposition distribution map.

7. Computation results

7.1. Tidal flow field

As for neap tide and middle tide, tidal water floods into the Qinzhou Bay in the northeastern direction while it floods into the Bay nearly in the northern direction during spring tide. As constrained by the shoreline and channel-shoal geomorphology tidal water propagates in the northwestern direction into the Yingling inlet and further into the inner bay, where it flows anticlockwise till stack water; then tidal water rushes into Yingling inlet and diverges among east, middle and west waterways; finally it leaves the Qinzhou Bay in the southwestern direction to the South China Sea (Figure 11).

Generally speaking, the tidal flow field in the Qinzhou Bay is characteristics of reciprocating flow in parallel to the major waterways, large scale eddies occur during flow reversal periods.

The computation results show that the ebb-mean velocities of spring tide and middle tide are all larger than the flood-mean velocities; while flood-mean velocity becomes larger than ebb-mean velocity during neap tide in the overall flow field of Qinzhou Bay.



Figure 11. a) Flood peak flow of spring tide in Qinzhou Bay, b) Ebb peak flow of spring tide in Qinzhou Bay.

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Figure 12. a) Upper-layer flood peak flow of spring tide in Qinzhou Bay, b) Middle-layer flood peak flow of spring tide in Qinzhou Bay, c) Lower-layer flood peak flow of spring tide in Qinzhou Bay.

Among three major tidal channels in the outer bay, the flood-mean and ebb-mean velocities of spring, middle, neap tides in the middle channel are all larger than those in the east and west channels; though flood-mean velocity in spring tide in the west channel is somewhat smaller than that in the east channel the flood-mean velocities in middle & neap tides in the west channel are all larger than those in the east channel; as for ebb-mean velocity, they are all larger in the west channel than those in the east channel. These data demonstrates that the west channel is the dominant channel for tidal water flowing into and out the Qinzhou Bay, the middle channel comes second and the east channel is third; ebb tide dominates in the west channel and middle channel but flood tide dominates in the east channel.

Generally speaking, flow velocity at the upper water layer is the largest and decreases from top to bottom (Figure 12). The depth-averaged residual flow is shown in Figure 13. Various-sized residual eddies occur in the Qinzhou Bay. Mean residual flow velocity in the Yingling inlet is around 0.15m/s with largest velocity of 0.489m/s, it is generally below 0.05m/s in other parts.



Figure 13. Depth-averaged residual flow in Qinzhou Bay.

7.2. Sediment transport

The suspended-sediment sources include those delivered by Maolingjiang river and Qinjing river and limited amount transported from the open sea, but the majority is eroded and re-

suspended in situ in the Bay. As a result, the spatial & temporal variations of suspendedsediment concentrations are in accordance with the processes of tidal flows.

Generally speaking, suspended-sediment concentrations are larger in major channels than those on shoals and intertidal zones (Figure 14), decrease from bottom to top. The majority of sediment delivered by Maolingjiang and Qinjiang rivers is deposited within the inner bay with limited amount of finer particles transported into the outer bay and deep water.



Figure 14. a) Suspended-sediment concentration field at flood peak of spring tide, b) Suspended-sediment concentration field at ebb peak of middle tide.

The computation results show that suspended-sediment concentration at spring tidal flood peak is 0.037 kg/m³, 0.021 kg/m³ at spring tidal flood stack, 0.034 kg/m³ at spring tidal ebb peak and 0.023 kg/m³ at spring tidal ebb stack, respectively, the mean spring-tidal concentration is 0.029 kg/m³; sediment concentration is 0.031 kg/m³ at middle tidal flood peak, 0.023 kg/m³ at middle tidal flood stack, 0.031 kg/m³ at middle tidal flood peak, 0.023 kg/m³ at middle tidal flood stack, 0.031 kg/m³ at middle tidal ebb stack, respectively, the mean middle-tidal concentration is 0.026 kg/m³; the sediment concentration is 0.013 kg/m³ at neap tidal flood peak, 0.013 kg/m³ at neap tidal flood stack, 0.013 kg/m³ at neap tidal flood stack, respectively. The mean neap-tidal concentration is 0.013 kg/m³. Generally speaking, suspended-sediment concentration is relatively low in the Qinzhou Bay.

The west channel has been the major channel to transport sediment from outer bay thought Yingling inlet to inner bay and vice versa; the middle channel comes second and the east channel contributes the least. The sediment discharges at ebb tide are all larger than those at flood tide in the three channels, demonstrating net sediment transport into the open deep water. The sediment discharges at spring tide in three channels are all larger than those at middle & neap tide, and the dividing ratio of west channel, middle channel and east channel is nearly 5:2:1 for spring flood tide and 7:5:1 for spring ebb tide, 4:2:1 for middle flood tide and 8:4:1 for middle ebb tide, respectively.

The sediment transport pattern is normally accordance with tidal flow asymmetry in three channels, that is, ebb flow strength and discharge are superior to flood flow strength and discharge.

7.3. Morphological evolution

7.3.1. 2009-year erosion and deposition

Due to lack of data on the deposit thickness distribution in Qinzhou Bay and considering that rock is exposed locally within the deep channel in Yingling inlet by strong tidal flows [8], the present study assumes the initial deposit thickness is 0.3m within the deep channel in Yingling inlet and 20m in other parts of the Qinzhou Bay. The morphological computation starts from year 2008.

The computed 2009 annual erosion & deposition distribution map is shown in Figure 15. It can be observed that erosions mainly occur within channels including three major channels in the outer bay, deep-water channel in the Yingling inlet and those in the inner bay while depositions occur at shoal & ridge area and at the end of channels. This asserts that tide flow is really the dominant force for maintaining and reforming the channel-shoal morphology in the Qinzhou Bay.

Generally speaking, eroded sediments exceed deposited sediment for the whole Qinzhou Bay with net erosion nearly up to 10.288 million m³. Except for the inner bay where net deposition occurs with a quantity of 3.190 million m³ net erosions all occur in the Yingling inlet and the outer bay, they are 2.999 million m³ and 3.503 million m³, respectively. Due to lack sediment supply, the offshore slope outside the Qinzhou Bay is also subjected to net erosion of 6.976 million m³, where erosion mainly occurs at the middle and southeastern part while deposition occurs at the southwestern part.

The total deposition in the west channel (bounded by -5m bathymetric contour, the same for middle channel and east channel) in the outer bay is roughly 490,887.486 m³, the total erosion is roughly 2,257,125.612 m³, and the net erosion is about 1,766,238.1 m³; the spatial mean deposition is 0.097m, the spatial mean erosion is -0.232m, the maximum deposition is 0.355m and the maximum erosion is -1.244m.

The total deposition in the middle channel in the outer bay is roughly 9,830.569 m³, the total erosion is roughly 551,595.451 m³, and the net erosion is about 453,285.88 m³; the spatial mean deposition is 0.073m, the spatial mean erosion is -0.394m, the maximum deposition is 0.157m and the maximum erosion is -1.785m. The erosion mainly occurs at the channel mouth connecting with the Yingling inlet.

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Figure 15. 2009-year annual erosion & deposition distribution map.

The total deposition in the east channel in the outer bay is roughly 499,259.028 m³, the total erosion is roughly 1,488,779.676 m³, and the net erosion is about 989,520.6 m³; the spatial mean deposition is 0.110m, the spatial mean erosion is -0.213m, the maximum deposition is 0.623m and the maximum erosion is -1.285m.

7.3.2. 2012-year erosion and deposition

The computed 2012-year annual erosion & deposition distribution map is shown in Figure 16. Eroded sediments still exceed deposited sediment for the whole Qinzhou Bay with net erosion nearly up to 10.469 million m³. The inner bay continues to accommodate net deposition of 2.832 million m³, net erosions still occur in the Yingling inlet and the outer bay, they are 0.809 million m³ and 4.161 million m³, respectively; the offshore slope outside the Qinzhou Bay is still subjected to net erosion of 8.331 million m³.

The total deposition in the west channel in the outer bay is roughly 240,510.501 m³, the total erosion is roughly 2,031,819.599 m³, and the net erosion is about 1,791,309.0 m³; the spatial

mean deposition is 0.063m, the spatial mean erosion is -0.185m, the maximum deposition is 0.232m and the maximum erosion is -0.889m.

The total deposition in the middle channel in the outer bay is roughly 32,702.536 m³, the total erosion is roughly 435,482.067 m³, and the net erosion is about 402,779.53 m³; the spatial mean deposition is 0.044m, the spatial mean erosion is -0.217m, the maximum deposition is 0.095m and the maximum erosion is -0.772m.



Figure 16. 2012-year annual erosion & deposition distribution map.

The total deposition in the east channel in the outer bay is roughly 356,241.632 m³, the total erosion is roughly 1,160,837.006 m³, and the net erosion is about 804,595.37 m³; the spatial mean deposition is 0.084m, the spatial mean erosion is -0.159m, the maximum deposition is 0.527m and the maximum erosion is -0.705m.

These data in the three channels reflect that the erosion and deposition in the three major channels in the outer bay has steadily decreased. In particular, the erosion length in the west

channel has increased substantially, leading almost to whole-channel erosion, and tidal channels have further developed in the inner bay.

7.3.3. 2020-year erosion and deposition

The computed 2020-year annual erosion & deposition distribution map is shown in Figure 17. Eroded sediments still exceed deposited sediment for the whole Qinzhou Bay with net erosion nearly up to 11.136 million m³. The inner bay continues to accommodate net deposition of 2.601 million m³, net erosions still occur in the Yingling inlet and the outer bay, they are 0.677 million m³ and 3.095 million m³, respectively; the offshore slope outside the Qinzhou Bay is still subjected to net erosion of 9.965 million m³.

The overall morphological evolution trend is that total erosion & deposition amount have dropped steadily in all parts of Qinzhou Bay though net deposition might moderately increase or decrease in different parts of the Bay.



Figure 17. 2020-year annual erosion & deposition distribution map.

The total deposition in the west channel in the outer bay is roughly 207,835.846 m³, the total erosion is roughly 1,685,565.419 m³, and the net erosion is about 1,477,729.5 m³; the spatial mean deposition is 0.074m, the spatial mean erosion is -0.141m, the maximum deposition is 0.311m and the maximum erosion is -0.475m.

The total deposition in the middle channel in the outer bay is roughly $17,775.557 \text{ m}^3$, the total erosion is roughly $296,870.467 \text{ m}^3$, and the net erosion is about $279,094.91 \text{ m}^3$; the spatial mean deposition is 0.025m, the spatial mean erosion is -0.145m, the maximum deposition is 0.049m and the maximum erosion is -0.405m.

The total deposition in the east channel in the outer bay is roughly 251,859.055 m³, the total erosion is roughly 929,903.211 m³, and the net erosion is about 678,044.15 m³; the spatial mean deposition is 0.069m, the spatial mean erosion is -0.118m, the maximum deposition is 0.431m and the maximum erosion is -0.412m.

7.3.4. 2040-year erosion and deposition

The computed 2040-year annual erosion & deposition distribution map is shown in Figure 18.



Figure 18. 2040-year annual erosion & deposition distribution map.

Eroded sediments still exceed deposited sediment for the whole Qinzhou Bay with net erosion nearly up to 13.915 million m³. The inner bay continues to accommodate net deposition of 1.063 million m³, but net deposition has occurred in the Yingling inlet with a value of 0.125 million m³, net erosion in the outer bay is 1.592 million m³, the offshore slope outside the Qinzhou Bay has been subjected to increased net erosion of 13.512 million m³.

The total deposition in the west channel in the outer bay is roughly 387,349.439 m³, the total erosion is roughly 1,114,549.259 m³, and the net erosion is about 727,199.81 m³; the spatial mean deposition is 0.098m, the spatial mean erosion is -0.103m, the maximum deposition is 0.335m and the maximum erosion is -0.429m.

The total deposition in the middle channel in the outer bay is roughly 37,682.474 m³, the total erosion is roughly 202,893.855m³, and the net erosion is about 165,211.38 m³; the spatial mean deposition is 0.054m, the spatial mean erosion is -0.099m, the maximum deposition is 0.310m and the maximum erosion is -0.379m.

The total deposition in the east channel in the outer bay is roughly 170,181.197 m³, the total erosion is roughly 420,256.804 m³, and the net erosion is about 250,075.6 m³; the spatial mean deposition is 0.051m, the spatial mean erosion is -0.051m, the maximum deposition is 0.271m and the maximum erosion is -0.259m.

The overall morphological evolution trend is that total erosion & deposition amount have continuously decreased, sub-channels haves occurred at the shoal between west channel and middle channel and new channel-shoal morphology has been developed within the inner bay (Figure 19).



Figure 19. Bathymetry maps of 2008 vs. 2040.

8. Long-term morphological evolution

The Qinzhou Harbor has used the east channel as its major navigation channel to deliver cargos. Two large-scale dredgings were performed within this channel, i.e. 2009/9-2002/12 with a total dredged sediment of 8.234 million m³, 2004/2-2008/12 with a total dredged sediment of 45.307 million m³ [9]. These two dredging activities have exerted profound influences upon the morphological evolution of the channel-shoal system in the Qinzhou bay. The present computation has just reflected this evolution process and trend. During the adjusting process, the deeper channels have experienced further erosion while the shallower shoals (ridges) have accreted further higher, and the overall stability of the channel-shoal system has been maintained without horizontal migration or sign of merging or perishing; the inner bay has not only accepted sediments delivered by Maolingjiang river and Qinjiang river, but also sediments from the outer bay has been transported into the offshore slope and deeper water by ebb tidal flows.

The magnitude of morphological adjustment by the above-mentioned channel dredging has been initially large but decreasing steadily with time. It could be estimated the morphological adjustment process at the outer bay would finished one hundred years later while other parts of the Qinzhou Bay might experience even longer adjustments. It should be clarified that such an estimation has assumed that no new engineering projects to be constructed and the computation conditions such as spatial bed thickness, horizontal & vertical sediment grading, shoreline configuration, tidal force and river discharges are unchanged.

9. Concluding remarks

Qinzhou Bay is characteristics of a unique dumbbell in shape, consisting of an inner enclosed bay, a trumpet-shaped outer bay and irregular rocky tidal inlet connecting them. Within the outer bay a complex channel-shoal (ridge) system has been present with the major channels serving as the navigation course for the Qinzhou Harbor.

FVCOM is a 3D unstructured grid, finite-volume coastal ocean model for the study of coastal oceanic and estuarine circulation, sediment transport and morphodynamics.. Having performed good calibrations of observed tidal water level, flow velocity and direction, suspended-sediment concentration at hydrographic sites [1] and morphological variation in the period of 2004 through 2008, the present study further investigates the diurnal tidal circulation including tidal asymmetry, residual eddy, and accompanying sediment transport processes in order to ascertain the water & sediment exchanges between the inner basin and the outer bay, especially, among the branching channels.

It is found that the inner basin has been acting as a sediment storage basin to accept sediments delivered by river flows and those by asymmetric tidal flows from the outer bay; Coriolis force together with rocks at the inlet mouth has controlled the dividing ratios of water and sediment among the branching channels, the west channel has been the dominant course for tidal flow and sediment to pass the outer bay, the middle channel comes secondly important and the east channel contribute the least.

Two large-scale dredging activities conducted in 2000/9-2002/12 and 2004/2-2008/12 in the east channel for deep navigation course development have exerted profound influence upon the morphodynamic evolution of the channel-shoal system. The erosion & deposition pattern, i.e. erosion in channels and deposition in shoals (ridges) has clearly demonstrated that tidal flow is the predominant force for maintaining and reforming the channel-shoal morphology; the dredging in the east channel has caused lasting erosions in the major channels in the outer bay, Yingling inlet and the inner bay as well as the offshore slope, meanwhile, depositions accumulate on shoals (ridges) and at the end parts of the channels.

Generally speaking, the overall channel-shoal system has been stable with channels becoming deeper and shoals becoming higher, and such a morphological adjustment process will probably finished over one hundred years later, if no new coastal engineering activity intervenes.

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References

- [1] Tianjing Coastal Zone Engineering Company (TCZC). (2009). Fengchenggang Nuclear Power Plant Summer Full Tide Hydrological Survey and Analysis. *Technical Report*, in Chinese.
- [2] Yan, X.-X., & Liu, G.-T. (2006). Study on deposition characteristics and channel siltation in offshore zone of Qinzhou Bay. *Journal of Waterway and Harbor*, 27(2), 79-83, in Chinese.

- [3] Li, G.-Z., Liang, W., & Liu, J.-H. (2002). Discussion on the source and transport tendency of silt in the Qinzhou Bay in terms of the dynamic partition zones of heavy minerals in the sediments. *Marine Science Bulletin*, 21(5), 61-68, in Chinese.
- [4] Chen, C., Liu, H., & Beardsley, R. (2003). An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: Application to coastal ocean and estuaries. *Journal of Atmospheric and Oceanic Technology*, 20(1), 159-186.
- [5] Warner, J. C., Sherwood, C. R., Signell, R. P., Harris, C., & Arango, H. G. (2008). Development of a three-dimensional, regional, coupled wave, current, and sedimenttransport model. *Computers and Geosciences*, 34, 1284-1306.
- [6] Wang, Y. H. (2007). Formula for predicting bedload transport rate in oscillatory sheet flows. *Coastal Engineering*, 54(8), 594-601.
- [7] Harris, C. K., & Wiberg, P. L. (1997). Approaches to quantifying long-term continental shelf sediment transport with an example from the northern California STRESS mid-shelf site. *Continental Shelf Research*, 17, 1389-1418.
- [8] Li, G.-Z., Liang, W., & Liu, J.-H. (2001). Features of underway dynamic geomorphology of the Qinzhou Bay. *Geography and Territorial Research*, 17(4), 70-75, in Chinese.
- [9] Wang, Y. H., Wang, C. H., Liu, D. B., & Lin, Y.-X. (2010). Preliminary study on channel stability in Qinzhou Bay. *Port & Waterway Engineering*, 8, 76-80, in Chinese.

