Regulation functions in the Beilun estuary by tidal numerical simulation

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Abstract. It is a relatively short distance from mountains to the sea for the Beilun river. Its runoff seasonally varies with strong flooding and less sand. The mangroves are unique and spread wildly in the estuary to maintain a stable riverbed by scouring the waves and currents. However, the regulation structures built along the estuary by both China and Vietnam were not well-designed according to the laws of flow and sediment movement. A numerical model has been developed to simulate the functions of the regulations in this paper. Today, the shape of the estuary is mostly formed by the regulation structures. The discharge ratio and velocity changes are displayed to reveal the effects of the regulations. Coriolis force is intended to drive the flooding and ebbing flow in different places, so the south passage usually becomes deeper and larger while the river island usually connects to the north shore in the northern portion of the earth. However, this phenomenon has not properly worked in this region, likely due to other manmade activities and the mangroves defending the shallows from scouring while the regulations are directing the flow currents.

1. Introduction

The Beilun estuary encompasses regions in both China and Vietnam, which can be difficult for field investigations. Information about its estuarine flow, sediment, evolution, and structures are not abundantly known. The riverhead is located at the south of the Hundred Thousand Mountains, which is famous for heavy rain in China with average annual precipitation of 3700 mm. The rains are generated by geographical effects as the warm moist air from the Indian Ocean rises there because of the mountains. Plentiful runoff carrying less sediment rashes out of the mountains from the steep slopes in summer. There are some branches that joint into the Beilun river at different locations, such as the Lufu river and other small brooks. So, the estuary is a semi-closed down valley bay with several tributary mouths. In the bay, there are not only broad shallow beaches but also mangroves wildly distributed along the tidal zone. It is valuable to study the flow or sediment movements of this estuary. A numerical model was built to simulate flow under different simplified conditions, such as branch blocking, passage narrowing, group of groins building, which can help to explain the regulations completed years ago and the current estuarine status.

2. Estuary status

The length of Beilun river is about 107 km and about 55.8 km of the river covers regions in both China and Vietnam. There are two passageways running into the sea, branched 350 m above the friendship bridge of China and Vietnam, where the right section flows south toward Vietnam and the left section flows east along the border. In this paper, the east estuary will be discussed. Salt water can reach the joint area as the mangroves can be found here. It means the whole left branch should belong to the...
estuary reach. However, the river mouth is usually limited to the downward portion of the very narrow waterway. It begins at the upper river island, Luling island, and ends at the coastline, which connects Wanwei island and Tra-co island from north-east to south-west. Thus, the estuary of Beilun river occupies an area of approximately 66.5 km$^2$, with 37.4 km$^2$ tidal beach included, the length is about 11 km, and the mouth breadth is approximately 6 km [1], see Figure 1.

**Figure 1.** Sketch of Beilun estuary (satellite remote sensing in year 1987).

Diurnal tide controls the estuary with an extreme tide range of 4.64 m and an average tide range of 2.04 m. The duration of the flood tide is longer than that of the ebb tide in the open mouth area, and the velocity of the ebb current is usually greater than the flood current. The salinity along the estuary is affected by fresh water from the upper stream. According to a field investigation [2] carried out in 1996, the salinity is 27.87% at the sea boundary area, 14.62% at the middle part at the Zuoshan port, 7.43% near the beginning of the estuary at Dudun river island, and 1% at the Dongxing bridge located about 3 km from the joint area.

The estuary is located in a warm and humid area, where annual averaged climate parameters are: a temperature of 22.5°C, rainfall capacity of 2220.5 mm, evaporation capacity of 1005 mm, and the relative humidity is 82%. The annual volume of runoff is about 5410 × 10$^6$ m$^3$ (same as 171.5 m$^3$/s), which mostly flows during the period from April to October, and especially during June to August. Approximately 80% of the total runoff discharges in the summer season. Sediment transport has the same distribution as runoff during the whole year. The average volume of sediment transport is 222 × 10$^3$ t/a, while an extreme season may be as high as 400 × 10$^3$ t/a [3–5]. Different volumes of annual runoff and sediment transport may be found in different reports, where a report [6] from the designing institute shows, with the Lufu river branch included, the total sediment transport is 640 × 10$^3$ t/a, while the runoff is 81.2 m$^3$/s.

The direction of the river trough near the estuary is from west to east and turns clockwise till the tip of the trough points toward the south east. In the estuary bay, the main trough joins with the channel from the north tributary and spreads south. According to a Chinese gulf investigation [7,8], the shoreline of the whole Beilun estuary is 77.25 km long, which includes a sand shore of 39.1 km, mangroves shore of 22.3 km, and manmade shore of 15.8 km. The north shore beaches are composed of sand, sand and mud, mud, and decayed rock. The marine geomorphology is complicated with river islands, shoals, sand bars, and sand ridges. The size of surface sediment from 0.125 mm to 0.154 mm is about 47.61%–69.47%, and from 0.065 mm to 0.076 mm, it is about 28.02%–30.54%. A contour map of average sediment size (in φ unit) is given as follows from an investigation in 2008 from March to May, see
Figure 2. It seems that many sizes of 0–7φ sediments are included in the estuarine area, and the total average size is about 2.62φ (0.163mm). The largest size is mostly distributed near the mouth area, east north of Tra-co island, and south of the Wanwei island. While the finer sizes are located in the south of the middle land (Wutou) and progressively increases toward the sea. The finest size (6φ) is usually found near the top of the bay or deep sea areas.

3. Evolution properties
The river reach near the mouth might silt during the dry season and scour during the flood season, but in contrast, the mouth area might silt and scour during opposite seasons. The salinity and climate of the Beilun estuary is ideal for mangroves, which grow here and cover almost all of the shore land. The tide zones with mangroves are usually ideal places for marine lives, and the stems and leaves of mangroves will weaken the flows or waves while the roots fix the earth. Considering the functions of mangroves and the minor sediment transport, the natural evolution of the Beilun estuary should be rather gradual and gentle.

Mangroves have caused accidents four times in this region: mangrove destruction on the embankment before 1949, enclosing mangroves for cultivation during the 1960s and 1970s, excessive deforestation in 1980 and 1981, and surrounding mangroves for shrimp farming in 1997 [9].

According to reports [1,10,11], complicated structures have been built along the estuarine shores and river islands. The right branch (south channel) is seemingly closed, the island in the left branch near the joint of the Lufu river has been connected with the north land, the second division in the left branch has been disturbed with the left passage half enclosed by a dike, and a group of groins have been built near the north shore. All these structures indicate that some drastic changes have occurred.

Dong [6] studied the evolution of the estuary using a suspended sediment numerical model, which has been certified by an investigation carried out in May 2011 with one tidal level and two tidal currents and suspended sediments. The field data of sediment concentration varies between 3–70 mg/L, which is a fine sediment situation. The river conditions have been set to match the field data, so it is easy to understand the model results, and the evolution of the estuary is in equilibrium with the changes in surface sediment no greater than 0.05 m/a. That work is helpful yet not enough for the flood season not concerned.

4. Function of estuarine structures

4.1. Introduction of math model
Enclosing or semi-enclosing passages in the estuary, river island reclamations are sensitive and may trigger changes in water and sediment transportation. To understand hydrodynamic changes caused by
the structures, a simplified model study is presented in this paper. A numerical hydrodynamic model with combined one-dimensional and two-dimensional analysis was built to focus on the estuary area, where flooding of both the trunk and branch streams are concerned [12].

4.1.1 Governing equations

The basic equations of two-dimensional tidal movement include the depth-integrated continuity equation and the momentum equation. The governing equations can be written as:

\[ \frac{\partial \zeta}{\partial t} + \frac{1}{C_\zeta C_\eta} \left[ \frac{\partial}{\partial \zeta} (Du_{\zeta}) + \frac{\partial}{\partial \eta} (Dv_{\zeta}) \right] = q_0 \quad (1) \]

\[ \frac{\partial u}{\partial t} + \frac{u}{C_\zeta} \frac{\partial u}{\partial \zeta} + \frac{v}{C_\eta} \frac{\partial u}{\partial \eta} + uv \frac{\partial C_{\zeta}}{\partial \eta} - v^2 \frac{\partial C_{\zeta}}{\partial \eta} = -f_4 - g \frac{\partial \zeta}{C_\eta} \frac{\partial E_4}{\partial \eta} + \frac{\partial A}{\partial \zeta} \frac{1}{C_\zeta} \frac{\partial E_4}{\partial \eta} + \frac{1}{C_\eta} \frac{\partial A}{\partial \eta} - g \frac{\partial u}{C_\eta} \frac{\partial A}{\partial \eta} - g \frac{\partial v}{C_\eta} \frac{\partial A}{\partial \eta} \]

\[ \frac{\partial v}{\partial t} + \frac{u}{C_\zeta} \frac{\partial v}{\partial \zeta} + \frac{v}{C_\eta} \frac{\partial v}{\partial \eta} + uv \frac{\partial C_{\eta}}{\partial \eta} - u^2 \frac{\partial C_{\eta}}{\partial \eta} = -f_4 f_1 - g \frac{\partial \zeta}{C_\zeta} \frac{\partial E_1}{\partial \eta} + \frac{\partial A}{\partial \zeta} \frac{1}{C_\zeta} \frac{\partial E_1}{\partial \eta} + \frac{1}{C_\eta} \frac{\partial A}{\partial \eta} - g \frac{\partial u}{C_\eta} \frac{\partial A}{\partial \eta} - g \frac{\partial v}{C_\eta} \frac{\partial A}{\partial \eta} \]

where

\[ A = \frac{1}{C_\zeta C_\eta} \left[ \frac{\partial}{\partial \zeta} (C_{u}) + \frac{\partial}{\partial \eta} (C_{v}) \right] \quad B = \frac{1}{C_\zeta C_\eta} \left[ \frac{\partial}{\partial \zeta} (C_{v}) - \frac{\partial}{\partial \eta} (C_{u}) \right] \]

where \( t \) is time, \( D \) is total water depth, and \( D = \zeta + h \), \( \zeta \) is tidal level, namely, the distance from the water surface to the mean water level. \( h \) is the water depth, namely, the distance from the seabed surface to the mean water level; \( \zeta \) and \( \eta \) are the vertical and lateral directions of the computational grid in the orthogonal body-fitted coordinate system, respectively; \( u \) and \( v \) are the flow velocity components of \( \zeta \) and \( \eta \), respectively; \( C_\zeta \) and \( C_\eta \) are the Lame coefficients; \( f \) is the Coriolis force coefficient; \( f = 2\omega \sin \varphi \), \( \omega \) is the rotational angular velocity of the earth; \( \varphi \) is the latitude; \( E_\zeta \) and \( E_\eta \) are the turbulent viscosity coefficient in directions of \( \zeta \) and \( \eta \), respectively; \( C \) is the Chezy coefficient; \( n \) is the Manning coefficient; \( g \) is the gravitational acceleration; \( q_0 \) is the source/sink strength on the unit area (including water intake, water drainage and pollutant discharge flow); and \( u^* \) and \( v^* \) are the flow velocities surrounding the source/sink nodes in the directions of \( \zeta \) and \( \eta \), respectively.

4.1.2 Boundary conditions

At the beginning, the water level and flow velocity at each point in the computational domain were the initial conditions of the computation:

\[ \begin{align*}
\zeta(t, \xi, \eta)_{t_0} &= \zeta_0(\xi, \eta) \\
u(t, \xi, \eta)_{t_0} &= u_0(\xi, \eta) \\
v(t, \xi, \eta)_{t_0} &= v_0(\xi, \eta)
\end{align*} \quad (4) \]

where \( u_0 \) and \( v_0 \) are the initial flow velocities of \( \zeta \) and \( \eta \), respectively. \( \zeta_0 \) is the initial tidal level, and these values are usually constants. \( t_0 \) is the starting computation time. Initial values are given through estimation and are inconsistent with the actual values. However, the deviation of the initial values gradually disappears with time during the computational process.

The tidal level boundary determined by field observation data was adopted as an open boundary. Slip conditions were used for the closed boundary. Therefore, the flow velocity of the outer normal direction of the boundary is zero in a fixed boundary.
4.1.3 Numerical method
The mathematical model was calculated with the Alternating Direction Implicit method (ADI) in the finite difference method. It shows that variables $\zeta$, $u$ and $v$ were under a staggered arrangement in the center and at two sides of the grids. When the difference discrete method was used for differential equations (1), (2) and (3), the time step $\Delta t$ at any time was divided into two half steps. In the first half step, the momentum equation in the direction of $\zeta$ was coupled with the continuity equation. Forward difference was used for the time partial derivative, and the central difference was used for the spatial partial derivative in the differential equation. Nonlinear terms were linearized. The implicit solution of $u$ and $\zeta$ and the explicit solution of $v$ were solved. Then, the solved $u$ and $\zeta$ values were substituted into the momentum equation in the direction of $\eta$. In the last half step, the moment equation in the direction of $\eta$ was coupled with the continuity equation. The implicit solution of $v$ and $\zeta$ and the explicit solution of $u$ were solved. After $v$ and $\zeta$ were solved, they were substituted into the momentum equation in the direction of $\zeta$. This method uses implicit and explicit solutions in multiple steps with advantages of both conserved. Thus, it has been extensively applied.

The upstream open boundary of the rivers uses a connecting mode between the one-dimensional and two-dimensional model. The connecting section uses the explicit lap-joint method. The upstream control section of the two-dimensional model is approximately 8.5 km to the north of the estuary and that of the one-dimensional model is approximately 35 km to the north of the estuary, where it is not influenced by tidal waves. The Preissmann implicit scheme was used to solve the one-dimensional model. The water level calculated by the two-dimensional model was explicitly transferred to the one-dimensional model, and the discharge calculated by the one-dimensional model was transferred to the two-dimensional model.

4.1.4 Roughness coefficient
The roughness coefficient, a comprehensive parameter in the tidal current calculation, is related to the sediment characteristics on the bed surface, water depth, and topography. It was calculated with an empirical formula (5) in this study:

$$n = n_0 + n'/D$$  \hspace{1cm} (5)

where $n_0$ is the basic roughness coefficient taken as 0.018-0.020 through the verification calculation. $n'/D$ is the correction term for the roughness coefficient, which was corrected with water depth $D$. This reflects the fact that the resistance of the beach surface is greater than that of the deep groove. When the water depth $D$ is smaller than 1.0 m, the maximum value of $n$ of the individual points is taken as 0.030. When water depth $D$ is greater than 1.0 m, it will be corrected according to formula (5); $n'$ is taken as 0.012.

4.2. Verification of the hydrodynamic model
4.2.1 Model set-up
The roughness coefficient, a comprehensive parameter in the tidal current calculation, is related to the computational domain of the mathematical model, the sea lateral boundary is set at 20 m depth area, and side boundaries of east and west are approximately vertical to the shores, the west one is located in the middle of the Tra-co island while the east one is located at the downward part of the Bailong peninsula, see Figure 3. The model covers 1012 km$^2$ with 32 km east-west and 35 km north-south, space steps vary from 8 m to 529 m and no more than 30 m in estuarine area.

4.2.2 Verification
A recent field investigation carried out in October 2013 with three level stations and eight current stations was collected for model verification. Submarine geography was simultaneously observed in most parts except the center of the estuary, so history and satellite remote sensing data were also used. Figure 3 shows the investigation stations, which did not surround the estuary well but can be used to control the seaside. Annual runoffs were adopted during the model verification and three times that of
the annual ones are assumed to represent the flood season. Part of the verifying curves are given in Figures 4 and 5.

![Figure 4. Curves of the water level verification.](image1)

![Figure 5. Curves of currents verification.](image2)

4.3. Schemes of simulation
Simulation schemes were designed according estuarine structures, see Table 1. Some are simplified, and some may be impractical.

| NO. | Name                  | Project description                                                                 |
|-----|-----------------------|--------------------------------------------------------------------------------------|
| Case 1 | Before project | Natural status with two bifurcations and all passageways are unobstructed.         |
| Case 2 | Right branch enclosed | Based on case 1, the first bifurcation is faded away with the south branch enclosed. |
| Case 3 | Land connection of Dudun | Based on case 2, the river island of Dudun is connected to the land at the west end in the north branch. |
| Case 4 | Right passage blocked | Based on case 3, the second bifurcation is treated with a semi-blocked dike in the right passageway. |
| Case 5 | Group of groins | Based on case 4, four groins are built in the north coast. |

4.4. Analysis of simulation
The emergence of the big river island, Luling island, forms the first bifurcation. The north branch is on the left side of runoff which maintains almost the same direction with the main trough of the upper stream. Another narrow and long river island can be found in the middle part of the north branch, which begins at the joint area of a side river, Lufu river, which may contribute to its evolution. Near the sea mouth of the north branch, there is a fish shaped shallow covered with mangroves. It is called Zhongjiansha shallow, part of which can dry out at low tide level but mostly submerged during high tide.

The characteristic sections are set to calculate the discharge ratio (shown in Table 2). On flood condition (three times annual runoff), the discharge ratios of north branch to south branch at the first bifurcation during the flood and ebb tides are 52:48 and 59:41, respectively. The north branch is the main passageway. The ratios of the north passage to south passage at the second bifurcation during the flood and ebb tides are 72:28 and 69:31, respectively, which shows that the north water way is the main one.
The coriolis force makes the flow turn right at the northern part of earth and tidal flood currents should drift towards the north for the propagation from east to west, but, on the contrary, the runoff drifts towards the south. This is common for departing currents in the estuary. The Coriolis effect shows greater power at the second bifurcation than the first one. The south branch has a big turn at the joint, but flood discharge prefers straight patterns, which may be the reason for this discharge ratio. The flow is stronger in the north branch after the south branch is enclosed. Figure 6 shows the velocity changes derived by the project. The changes are clearer in the ebb tide process because the flood tide is weak during summer. The flood tide currents are weaker in the upper stream of the first bifurcation too. Tidal energy is typically large at sea, and it will find another way to propagate if one way is closed. The model is designed with a fixed bottom and cannot enlarge this section by scouring, which may limit the tidal volume. The surface sediment varies the grade size, where both the bed and river island trend to movable, which is a stable risk, so it is understandable to connect the river island to land. The land connect project helps the flooding of the Beilun river undisturbed by the Lufu river discharge. After the southern passageway is blocked at the second bifurcation, the ratio of ebb discharge decreases from 31% to 24% while the flood discharge ratio decreases from 30% to 26%. It is clear the northern passageway will pass through more water and sediment. The north shore is the concave bank washed away under both flooding and tide currents and can become endangered without protection from mangroves. The four groins should be engineered to protect shores. After this project, the north flood tidal ratio decreased from 74% to 73% and ebb tidal ratio decreased from 76% to 74%. The groin area velocities clearly weakened, but the discharge ratio of the passageway changed very little, see Figure 6.

| No. | Tide | First bifurcation | Second bifurcation |
|-----|------|-------------------|--------------------|
|     |      | Northern branch   | Southern branch    | Northern passage | Southern passage |
| Case 1 | Flood | 52                | 48                | 72               | 28               |
|       | Ebb   | 59                | 41                | 69               | 31               |
| Case 2 | Flood | 100               | 0                 | 70               | 30               |
|       | Ebb   | 100               | 0                 | 69               | 31               |
| Case 3 | Flood | 100               | 0                 | 70               | 30               |
|       | Ebb   | 100               | 0                 | 69               | 31               |
| Case 4 | Flood | 100               | 0                 | 74               | 26               |
|       | Ebb   | 100               | 0                 | 76               | 24               |
| Case 5 | Flood | 100               | 0                 | 74               | 26               |
|       | Ebb   | 100               | 0                 | 74               | 26               |
5. Discussions

It is usually the north river island that joins with land based on Coriolis forces in the northern portion while the southern passage way becomes deeper and wider. The north shore in the Beilun estuary needs structures to protect, which is a special situation due to its contrary evolutionary law. Public research results show that the evolution of the Beilun estuary has been disturbed by many structures and human activities, although the shape and situation have not been significantly changed according to satellite remote sensing, which may be strongly related to the wide mangrove distribution. A math model built in this paper has been used to understand the structures both from regulation theory and practical experience. Although the field data is not abundant and some structures may not be accurate, several conclusions can be drawn:

1) The runoff trends flow straight in the flood season in the river part of the estuary, and current ways of flood and ebb tides have departing effect, which may be stronger in the open sea area than the river.
2) Surface sediment is easy to move during the flood season for the narrow river channel, and structure protection is needed in the river island and shore land without mangroves.
3) Submarine geography may change during the flood and dry seasons, but more field investigation is necessary.
4) Estuarine management and development should be made by China and Vietnam, and regular field data collection should be carried out.

6. References

[1] Hu H and Shen H T 1994 The research on channel processing of Beilun Estuary (Beijing: State oceanic Administration People's Republic of China)
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