Numerical study of sediment transport in Thu-Bon estuary and coastal areas of Hoi-An City

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Abstract. The area of Cua-Dai estuary and the coastal areas of Hoi-An City have experienced complicated erosion and sedimentation in recent years. Along the coast of Hoi-An, erosion often occurs, whereas in the area of Cua-Dai River, there is an accretion phenomenon that obstructs the waterway navigation from Cua-Dai to Cu-Lao-Cham. Occurrence of sand dunes in the offshore location of Cua-Dai has been recorded at a number of times in recent years. Studying the process of bed morphological change due to the sediment transport in the Thu-Bon river and the influence of monsoons in the area allows to explain the above phenomenon thus an in-depth study to propose appropriate solutions. This study used the numerical model Telemac which combines the hydro-morphodynamic and wave modules. The simulation results show that the main trend of coastal currents caused by tides and waves tends to go southward, leading to coastal erosion especially in the northeast monsoon season as well as sedimentation in the estuarine area. In addition, the model also shows the crucial role of waves in shoreline erosion, with the degree of erosion in the north coast near Cua-Dai being more severe than the southern coast, through the formation of local eddy flow on the north coast.

1. Introduction

Thu-Bon estuary (Cua-Dai) is the outlet of the Vu-Gia – Thu-Bon river system in Quang-Nam province and Da-Nang city. This is a type of estuary that opens and closes seasonally and moves cyclically under the combined effects of river and sea, thus the morphological evolution is quite complicated. Fluctuation processes are controlled by wave characteristics, beach form, sediment characteristics, and resultant near-shore circulation. In terms of morphology, the estuary forms mainly with loose materials consisting of medium to coarse sand and is prone to the water currents. In terms of hydrodynamics, the river is under the combined influence of both marine and river hydrological regimes, but has very distinct seasonal characteristics: opening and eroding river banks during the flood season with high discharge rate; and accreting quickly in the dry season with a duration of about eight months a year, causing difficulties for navigation and economic activities when the locality has to continuously dredge to ensure the depth of navigation.

The interaction between sediment, ocean waves and currents over a range of spatial and temporal scales generate a variety of morphological features observed in the coastal areas. These range from...
wave ripples [1], sandbars [2] and large scale bedforms [3] [4]. Various projects at different geographic scales have been undertaken to study Cua-Dai, with an aim of better understanding the effects of ocean impacts and sediment transport trends to propose appropriate measures for the local economic development. Some highlight international studies are Vietnamese – Indian project (2002–2003) “Study on erosion/deposition phenomenon in Hoi An coast”, Vietnamese – Holland project (2005–2007) “Study on the environmental impact assessment from opening/closing of Tu Hien Inlet phenomenon in Tam Giang-Cau Hai Lagoon”, Vietnamese – Sweden project (2005–2011) “Study on the coastal evolution and sustainable management in Vietnam” or recently AFD (France) and GIZ (Germany) projects that focused on coastal erosion in Hoi-An and proposed some hard and soft solutions to mitigate this phenomenon. Concerning the national projects, there are KC.09.24/06–10 “Study on erosion/deposition processes along South Central Vietnamese coast” or Quang Nam Province project (2013–2015) “Study on coastal erosion/deposition processes in Quang Nam province and proposal of the necessary measures for coastline protection”. However, access to the full report of these projects is still limited. For published documents in the last decade, many studies monitored the shoreline dynamics of the Cua Dai estuary by using field survey data, geographic information systems techniques, and multi-temporal satellite remote sensing images [5] [6] [7]. Besides carrying out field investigations, several numerical models for explanation and prediction of erosion/deposition processes were applied [8] [9]. However, these studies have not focused on the mechanism of formation and loss of sand dunes in the estuary.

Since waves and nearshore currents cause sedimentation and morphological changes at the estuaries, this research aims to understand the mechanism of the erosion process in Hoi-An beach. The formation and loss of sand dunes in the offshore of Cua-Dai is a physical phenomenon that occurs over a long period (with a cycle of years). Therefore, in order to study this phenomenon, numerical modeling has many advantages over the laboratory scale models. This study uses numerical modeling methods to simultaneously describe 3 related physical phenomena: hydrodynamic model in river and coastal areas, wave model and morphological model. The study outcomes can provide essential information for establishing the operation institution of upstream reservoirs and sand mining in Vu Gia - Thu Bon, as well as recommendations of soft / hard measures to protect Cua-Dai beach but not leaving the bad effects on neighborhoods.

2. Study area and methods

2.1. Study area

The study area includes the downstream network of Thu-Bon river, a part of the north coast bordering Son-Tra peninsula, with a length of about 45 km along the coast and an average width of about 40 km from the shore. The area is about 2594 km², including 20 km of downstream river of Vu Gia-Thu Bon system, 5 km along the coastline to the north and the south of the estuary, and 4 km away from the coast. Cua-Dai River mouth is a large estuary area where the Thu Bon River flows into the East Sea. In regard to climate, this site belongs to the tropical climate zone, which is affected by the cold northern wind and has only two main seasons: rainy and dry. The average rainfall ranges from 2000 to 2500 mm, but it is unevenly distributed over time and space. The rainy season mainly occurs between September and December (representing about 80% of the total annual rainfall) and coincides with the tropical typhoon season.

This zone is described by 64571 unstructured triangular elements with the largest mesh of 2000 m (offshore element) whereas the smallest is 50m for the elements in Thu-Bon river (see figure 1). A larger scale of Cua-Dai River mouth can be seen in the figure 2 in which the bed level of this area is also represented.
2.2. Method

In this study, we used the open-source hydrodynamics software TELEMAC 2D, coupling with two-dimensional morphologic module called “SISYPHE” and spectral wave propagation module called “TOMAWAC” to evaluate the erosion mechanism in Cua-Dai estuary area under the combined and complex effects of waves and tides. Users can interfere with these modules using Fortran algorithms to achieve specific computational purposes. Telemac model was developed in 1987 by the Electricity of France (EDF) Company, with the participation of many research organizations around the world. The
Telemac-2D module is used to simulate free surface flows in 2 dimensions of horizontal space [10]. It solves the Saint-Venant equations using the finite-element or finite-volume method as follows:

Continuity equation:
\[
\frac{\partial h}{\partial t} + \text{div}(h \vec{U}) = q
\]

Momentum equation along x axis:
\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial Z}{\partial x} + F_x + \frac{1}{h} \text{div}[h \nu \text{grad}(u)]
\]

Momentum equation along y axis:
\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial Z}{\partial y} + F_y + \frac{1}{h} \text{div}[h \nu \text{grad}(v)]
\]

where \( h \) (m) –depth of the flow, \( u \) & \( v \) (m/s) – depth-averaged velocity components along \( x \) & \( y \) axis of velocity \( \vec{U} \), \( q \) (m/s) – discharge, \( Z(x) \) – free surface elevation, \( F_x, F_y \) (m/s²) – external forces (except gravity, for example, the Coriolis force, wind ... per mass unit along \( x \) & \( y \) axis, \( \nu \) (m²/s) – coefficient of velocity diffusion.

By means of a finite-element type method, TOMAWAC solves a simplified equation for the spectro-angular density of wave action, representing the variation of the directional spectrum density by the following equations:
\[
\frac{\partial N}{\partial t} + \frac{\partial \vec{x} N}{\partial x} + \frac{\partial \vec{y} N}{\partial y} + \frac{\partial k_x N}{\partial x} + \frac{\partial k_y N}{\partial y} = Q(k_x, k_y, x, y, t)
\]

with \( N(\vec{x}, \vec{y}, k, t) = N(x, y, k_x, k_y, t) \) indicates spectrum density of wave. \( \vec{x} = (x,y) \) indicates position in Cartesien cordinates. \( \vec{k} = (k_x, k_y) = (k \sin \theta, k \cos \theta) \) is wave number vector, \( \theta \) denote the wave propagation direction
\[
\dot{\vec{g}} = \frac{\partial g}{\partial t} + \frac{\partial g}{\partial x} \frac{\partial x}{\partial t} + \frac{\partial g}{\partial y} \frac{\partial y}{\partial t}
\]

Sediment transport and bed change module SISYPHE can be used to model complex morphodynamic processes for different flow conditions, sediment size classes and sediment transport modes. SISYPHE is applicable to non-cohesive sediments that can be uniform or non-uniform, as well as cohesive sediments and sand mud mixtures. The sediment transport in 2D model is described by the following equation:
\[
\frac{\partial h C}{\partial t} + \frac{\partial (h UC)}{\partial x} + \frac{\partial (h VC)}{\partial y} = \frac{\partial}{\partial x} \left( \rho \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho \frac{\partial C}{\partial y} \right) + E - D
\]

\[
(E - D)_{ref} = \omega_s (C_{eq} - C_{ref})
\]

where \( C = C(x,y,t) \) is the concentration of sediment in vertical direction \( h = Z_e - Z_f = Z_e - Z_{ref} \) is the river stage; \( E \): erosion rate; \( D \): accretion rate; \( (U,V) \): average velocity in \( x, y \) direction; \( C_{eq} \) is equilibrium sediment concentration close to bed; \( C_{ref} \) is sediment concentration close to bed; \( \omega_s \) is settling velocity.

2.3. Boundary conditions
The study area includes 2 discharge boundaries on two major tributaries located at about 12km towards the upstream of Cua-Dai estuary: a large branch near Cau-Lau bridge and a small branch in the upstream of Cua-Dai bridge. Each branch is assigned with two discharge rates respectively: the wet period (October - December) with \( Q_1 = 700m^3/s \) and \( Q_2 = 100m^3/s \), and the dry period (March - July) with \( Q_1' = 250m^3/s \) and \( Q_2' = 50m^3/s \). The river stage on the open boundary in the East Sea is from the astronomical tides with the 9 main waves (\( S_2, N_2, K_2, M_2, K_1, O_1, P_1, Q_1 \) and \( M_4 \)) extracted from the OTIS database with a resolution of 1/30°.
The spatial-temporal variations of wave and wind data during the simulation period are from the NOAA's database. Typical wave height in the offshore area ranges from 1.5m to 2.5m and gradually decreases to about 1m in the estuary area. At the location near the North and South shores of Cua-Dai, wave values are below 0.5m (see figure 3).

![Typical wave height evolution at different locations during the simulation period from October 1, 2014 to October 11, 2014.](image)

**Figure 3.** Typical wave height evolution at different locations during the simulation period from October 1, 2014 to October 11, 2014.

During the period between winter and early summer, mostly the Southeast wind blows to the Northwest. The maximum wind speed up to 12.7m/s occurs during the Northeast monsoon (blowing from the sea in winter). In the summer, the area is influenced by the Southwest monsoon with hot and dry westerly wind (from Laos to Central Vietnam) (see figure 4).

![Typical wind rose chart in 2014 at Cua-Dai River mouth, taken from NOOA 2014 data: (a) March 2014, (b) November 2014.](image)

**Figure 4.** Typical wind rose chart in 2014 at Cua-Dai River mouth, taken from NOOA 2014 data: (a) March 2014, (b) November 2014.

The sediment is considered as non-cohesive sand and the distribution is assumed to be uniform throughout the study area. According to the sediment monitoring, particle sizes were divided into three typical classes: 0.125mm, 0.6 mm, and 1.0 mm; with a ratio of 40%, 30%, 30%, respectively (from AFD project). For sediment flux at the inflow boundary, unit suspended-sediment concentration (m³/s) of three particle classes at the two tributaries are shown in table 1.
Table 1. Sediment flux at the inflow boundary (m²/s).

| Tributary                                | $Q_{0.125mm}$ | $Q_{0.6mm}$ | $Q_{1mm}$ |
|------------------------------------------|---------------|-------------|-----------|
| Large branch (behind Cau-Lau bridge)     | $2.644\times10^{-10}$ | $3.526\times10^{-10}$ | $2.644\times10^{-10}$ |
| Small branch (upstream of Cua-Dai bridge)| $6.545\times10^{-11}$ | $8.727\times10^{-11}$ | $6.545\times10^{-11}$ |

3. Model calibration and validation

3.1. Hydrodynamic

The hydraulic model is calibrated and validated using the monitoring data at some typical locations in the wet and dry seasons. The model is sensitive to friction, eddy viscosity, Coriolis as well as space discretization. These parameters have to be adjusted to give the best fit of the model results to field observations for the same location and period of time. The simulation duration is taken within one month to analyze the short-wave components, based on the insignificant impact of the long-wave components on the short-term simulation results. Figure 5 and 6 represent respectively the comparison between observed and simulated stages in October 2014 (model calibration) and in March 2014 (model validation). Accordingly, with the one month water levels, there are 12 tidal wave components. The results from tidal harmonic analysis using the T_tide code of Pawlowicz et al. [11] showed that there is high consistency (> 90%) in amplitude and phase between the simulated and observed data (see table 2 and table 3). Tidal waves in both the calibrated (October 2014) and validated period (March 2014) showed that the principal lunar semidiurnal constituent ($M_2$), lunisolar diurnal constituent ($K_1$) and the lunar diurnal constituent ($O_1$) are dominant with an amplitude of 0.15m - 0.2m but there is a variation in phase between seasons. The wave height $H_{m0}$ during wet season can reach 2.5m at offshore locations, higher than in dry season. This result is consistent with the previous measurement data.

Figure 5. Comparison between observed and simulated stages in October 2014 (Model calibration).

Table 2. Harmonic analysis results for stages in October 2014 (Model calibration).

| Tide | Observed data | Simulated results |
|------|---------------|-------------------|
|      | Amplitude (m) | Phase (degree)    | Amplitude (m) | Phase (degree) |
| $K_1$ | 0.1908        | 71.2              | 0.1844        | 78.1           |
| $M_2$ | 0.1838        | 264.6             | 0.1903        | 252.4          |
| $O_1$ | 0.1543        | 34.6              | 0.1491        | 50.5           |
| $S_2$ | 0.0747        | 335.2             | 0.0928        | 334.1          |
| $N_2$ | 0.0417        | 311.1             | 0.0458        | 313.7          |
| $Q_1$ | 0.0298        | 95.4              | 0.0317        | 113.5          |
| $NO_1$ | 0.0206       | 141.3             | 0.0162        | 201.0          |
Table 3. Harmonic analysis results for stages in March 2014 (Model validation).

| Tide  | Observed data | Simulated results |
|-------|----------------|-------------------|
|       | Amplitude (m)  | Phase (degree)    | Amplitude (m)  | Phase (degree) |
| MO3   | 0.0117         | 202.7             | 0.0182         | 305.1          |
| J1    | 0.0072         | 206.7             | 0.0149         | 208.1          |
| MK3   | 0.0057         | 231.4             | 0.0186         | 312.8          |
| M4    | 0.0041         | 117.1             | 0.0159         | 157.6          |

3.2. Wave

The wave model is also calibrated using the monitoring data at some typical locations in October – November 2014 and then validated in October 2016. Figure 7 and figure 8 show respectively the comparison between observed and simulated wave height HMw as the calibration and validation of the wave model.
4. Study of sediment transport

4.1. Sediment transport

Simulation results reveal that the sediment transport occurred in all directions with the highest amount at the estuary. However, we noted a more significant sediment rate in the North whereas the sediment is shifted very far to the South coast of Cua-Dai although with a low amount (see figure 9 and 10).
Figure 10. Distribution of sediment transport in the rainy season (m²/s), at different locations: (a) at the estuary, (b) 1000 m from the estuary along the river axis.

4.2. Bed morphology evolution
In figure 11, the simulation of sediment transport for 2 different periods (rainy season versus dry season) are presented. In addition, to investigate the morphological change of Thu-Bon estuary, three study sections have been applied (1-1, 2-2 and 3-3). The results show that erosion occurs mostly in the north coast of Cua-Dai estuary (about 4.5km) and happens more seriously in the Northeast monsoon period (October 2014), with the maximum erosion depth of about 0.85m (at section 1-1). In addition, sedimentation is formed in the offshore of Cua-Dai towards Cu Lao Cham, which is consistent with the observed situation in recent years.

Figure 11. Simulation results of erosion (accretion) (a) from October 1, 2014 to November 15, 2014; (b) from March 1, 2014 to April 15, 2014.

4.3. Impact of wave
One of the factors that can be detrimental to the phenomenon of coastal erosion in Hoi An comes from the action of waves. To elucidate the influence of this factor, we tested a scenario during rainy season in which the wave effect is ignored. The simulation results of the change of bottom elevation are presented in figure 13. Comparison of the results between two scenarios (with and without waves) shows the crucial role of waves in coastal erosion phenomenon in Hoi-An city. In the case of ignoring the influence of waves on the Hoi An coast, especially on the northern shore, the erosion is greatly reduced and the beach is almost stable.
Figure 12. Comparison of bed morphology evolution during the rainy season (continuous line) and dry season (dash line). Left: section 1-1 (north); right: section 3-3 (south). Note: $\Delta Z < 0 \rightarrow$ erosion, $\Delta Z > 0 \rightarrow$ accretion.

Figure 13. Simulation results of erosion (accretion) from October 1, 2014 to November 15, 2014 without the presence of waves.

5. Conclusion
The simulation results show that the main trend of coastal currents caused by tides and waves tends to go southward, leading to coastal erosion in the north coast, especially during the northeast monsoon season with a rate up to one meter in October 2014. This is not the case for estuarine area with a sediment transport of 0.0002 m$^2$/s and sedimentation of about 0.3m is observed. In addition, the model also shows the crucial role of waves in shoreline erosion, with the degree of erosion in the north coast near Cua-Dai being more severe than the southern coast, through the formation of local eddy flow on the north coast.

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