



STUDY CHARACTERISTICS OF HYDRODYNAMICAL AND MORPHODYNAMICAL REGIMES IN THE NHAT LE ESTUARY AREA, QUANG BINH, USING DELFT3D MODEL

Nguyen Hong Lan¹, Dao Dinh Cham², Vu Van Lan¹

¹Hanoi University of Natural Resources and Environment, Vietnam

²Institute of Geography - Vietnam Academy of Science and Technology (VAST)

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Abstract

This work presents the hydrodynamics and morphodynamics regimes of the Nhat Le estuary based on the collected data and numerical simulations using Delft3D model. Based on a numerical model, the main physical processes governing estuary morphology, including tides, waves and freshwater runoff, have been simulated and analyzed for better understanding the morphological evolution of the estuary. The simulation results showed that the study area has quite similar tidal regimes, most of which have irregular diurnal properties; storm and monsoon surges in this area often occur during the year; the time of rising water due to the monsoon lasts from October of the previous year to March of the following year, the highest is in December, coinciding with the period when the dominant wave direction is the northeast, accounting for over 60 % with height of 1.25 m, directly affects the shoreline causing coastal erosion in the South Central Coast.

Keywords: Coastal zone; Nhat Le estuary; Quang Binh; Erosion.

Corresponding author. Email: nhlan@hunre.edu.vn

1. Introduction

Researching the coastal development process is the study of the interactions between the coast and hydrodynamic factors and human impacts [1]. Coasts or estuaries are sensitive and constantly changing under the influence of waves and currents. The results of the hydrodynamical processes are changing the amount of sediment in the water and the direction of their transport at the coast. Therefore, the study of hydrodynamics aims to identify the rules of coastal evolution, serving to forecast

and effectively respond to the coastal erosion. Research on modern sediments is a direction of hydrodynamic methods, studying the distribution, content in percent of grain grade size, selectivity of the seabed surface sediments, related to hydrodynamic processes. However, studies on coastal development under natural conditions must be the combined result of many research fields [3].

The study of determining the mechanism and causes of coastal erosion - accretion, alluvial estuary of Nhat Le river, Quang Binh province is an urgent

work to elucidate the process of coastal erosion, accretion of Nhat Le river mouth. The cause of erosion - accretion is a combination of influencing factors related to the natural evolution of the estuary coastal zone and human impacts. It can be seen that at a particular shoreline

with a defined geological structure and rock composition, erosion or accretion is caused by one of three groups of causes: exogenous, endogenous and anthropogenic, or a combination of two or all of those reasons.



Figure 1: Estuary of Nhat Le and locations of observations (water level at Dong Hoi tidal hydrological station, AWAC (Acoustic Wave and Current) system was used to measure waves and currents)

This article discusses detailly the impact of driving processes and the morphological behavior of the estuary in the tropical monsoon regime using measurement data and results of numerical models. The study of the influence of seasonal river runoff, tides, wave dynamics on sediment transport and morphological changes in the estuary based on data and numerical modeling clearly shows the pattern of erosion and accretion in the estuary, which makes it possible to explain the formation and development of sand bars in the estuary. Therefore, this study aims to better understand the main influencing processes and morphology of the estuary through data collection and

numerical modeling of hydrodynamics, sediment transport and morphological changes in the estuary.

2. Research area

The Nhat Le estuary is located in the Quang Binh province in Central Vietnam and is the estuary of Kien Giang river, that has a basin area of 2,650 km². It is located in the low-lying area of the Central Coast of Vietnam and plays an important role in the socio-economic development of the province and region (see Figure 1). The topography of Kien Giang river basin is mainly hilly and low, the average elevation of the basin is 234 m and the slope is 20.1%. This estuary is the entrance to the

harbor and shelter from storms for about 750 fishing vessels in the region. Under the influence of processes of tides, waves and river runoff in the tropical monsoon zone, the estuary morphology is very dynamic and has unique features.

Mathematical modeling: The process of sediment transportation in Nhat Le estuary under the influence of upstream currents and sea processes such as tides and waves is modeled by the Delft3D model developed by Delft hydraulics laboratory [4]. Wave propagation and variation are modeled by Delft3D-WAVE module on the basis of SWAN model (Simulation Wave Nearshore). The changes of water level fields, flow velocities, sediment transportation and bottom variation were modeled using the Delft3D-FLOW module. The resulting water level, flow and bottom topography from Delft3D-FLOW are used as input conditions for the Delft3D-WAVE wave model. The results of wave and flow, caused by wave, calculated from Delft3D-WAVE are used as input data for Delft3D-FLOW to calculate current, sediment transportation and bottom change in the next steps. For getting an idea of the leading processes and the mechanism of morphological changes in the Nhat Le estuary, a 2D numerical model of the estuary in Delft3D was developed [5]. The SWAN model solves the impact balance equations according to the difference scheme for five independent variables of time, geographical space and spectral space (x, y, t, σ, θ). A detailed explanation of the processes involved and the numerical methods used in the SWAN model can be found in [2] and technical documentation of the SWAN model (Delft3D-WAVE user manual).

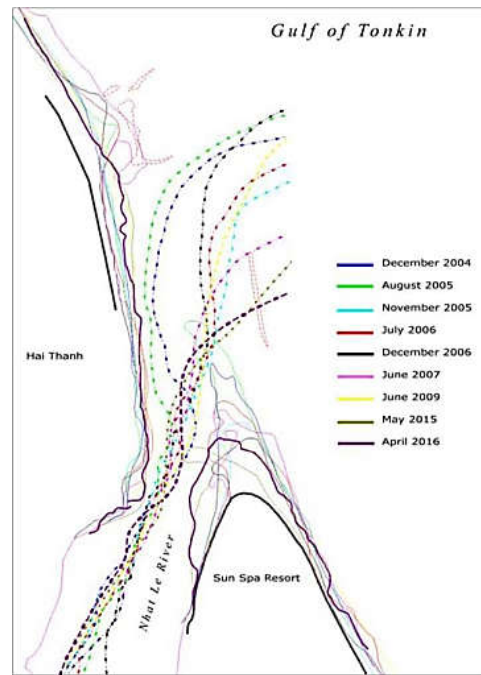


Figure 2: Variations of the coastline (solid line) and main channel (dashed line) at Nhat Le, based on survey data. The colors indicate the date of observation

Data collection: The requirement data for the simulation model of the sediment transport should include both of hydrodynamical and wave model data and the sediment content and characteristics data. Topographical data of the study area are one of the important input conditions that greatly affect the calculation results. To calculate the wave and current fields in the study area, the research is based on the 1:50,000 scale topographic map, created by the Institute of Geography (IG) - Vietnam Academy of Science and Technology (VAST). The model includes data on river discharge and tides and waves at sea. The boundary data is the discharge process, extracted from the MIKE model (Provided by DHI Institute of Water and Environment) [6], tidal data for the offshore boundary is obtained from wave data and Global tides for the following offshore boundary. The wave data included in the model are the

reanalyzed NOAA waves data at position (107°E, 17.5°N). Field data in the Nhat Le estuary were extensively collected by the Institute of Geography between 2005 and 2016 years, included: bottom topography, waves, tide levels, river runoff and sediment particle sizes. It can be seen from Figure 2 that the decrease in the main channel and the development of the sand bar is very dynamically in different years and seasons.

Numerical modeling: The numerical model is a pair of Delft3D-FLOW and Delft3D-WAVE models using SWAN (see Delft3D-WAVE user manual) to account for the effects of tides, surges and river runoff. Figure 3 shows the model area, computational grid, estuary bathymetry and the location of the

inflowing river flow boundaries and observation stations. The topography data is surveyed at a scale of 1:5000 in Nhat Le estuary area and 1:50.000 in the deep sea. The computational grid for the Nhat Le estuary, its rivers and the adjacent continental shelf consists of 512×329 elements. The grid spacing is up to 15 m in the estuary and river channels, then it becomes coarser with distance from the coast to open spaces. The maximum grid spacing at the outer boundaries of the shelf is about 300 m (see Figure 3). The cells of the net in the main channels of the estuary were 15 m long and the outer cells were up to 300 m in length. Fine mesh of bathymetry was performed at 30 m resolution for the Nhat Le estuary and 500 m resolution for the offshore zone.

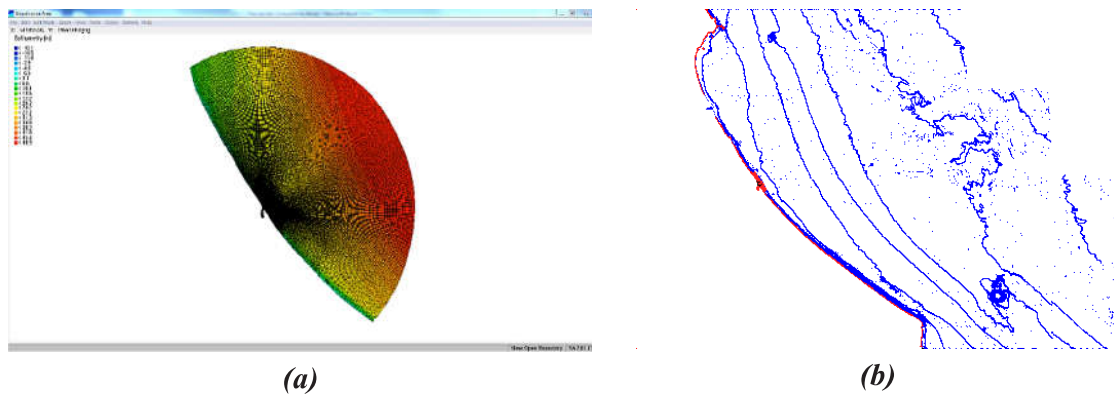


Figure 3: Computational domain and grid (a) and topography map (b) of Nhat Le study area

The boundary conditions of the impacts from the high seas were associated with astronomical tides. Based on the TPXO 8.0 global ocean tide model [7, 9], ten tidal components Q_1 , O_1 , P_1 , K_1 , M_2 , S_2 , K_2 , N_2 , MF , MM were recognized as dominant and used as open boundary conditions of the model in this area. Corresponding to each sea segment will correspond to different harmonic constants. The model used a 17-year series of measurement data from TOPEX/Poseidon, Jason-1 and Jason-2 satellite

data sources to analyze the residual composition of sea tide level. Based on satellite data, the harmonic coefficients are calculated.

The riverside boundary is the discharge data extracted from the 1-dimensional model. The marine boundary conditions for the waves are the parameters of the deep-water wave from the WAVEWATCH II model (Ocean Wave Model developed at NASA, Goddard Space Flight Center 1992). The upstream

boundary conditions included river runoff calculated for 8 tributaries using the NAM (Nedbor Afstromnings Model) precipitation runoff model in conjunction with MIKE 11 released by DHI (2012). Data for the NAM model included time series of precipitation data at the Kien Giang hydrological station (17°00'40.89N, 106°44'09.94E), time series of average daily air temperature, wind speed, relative humidity and solar radiation at the Dong Hoi meteorological station (17°28'19.83N, 106°37'27.32E) to simulate daily evaporation and water

discharge in the basin. The preliminary parameter set of the model is the Manning roughness coefficient for the entire calculation domain, which varies in the range from 0.03; average grain size $d_{50} = 0.3$ mm; simulation period: from May 1 to June 1, 2015.

As mentioned above, setting up the sediment transport model for the study area only has the characteristics of the sediment and morphology of the study area to simulate the evolution of the inshore sediment transport due to the influence of the river of waves and tides.

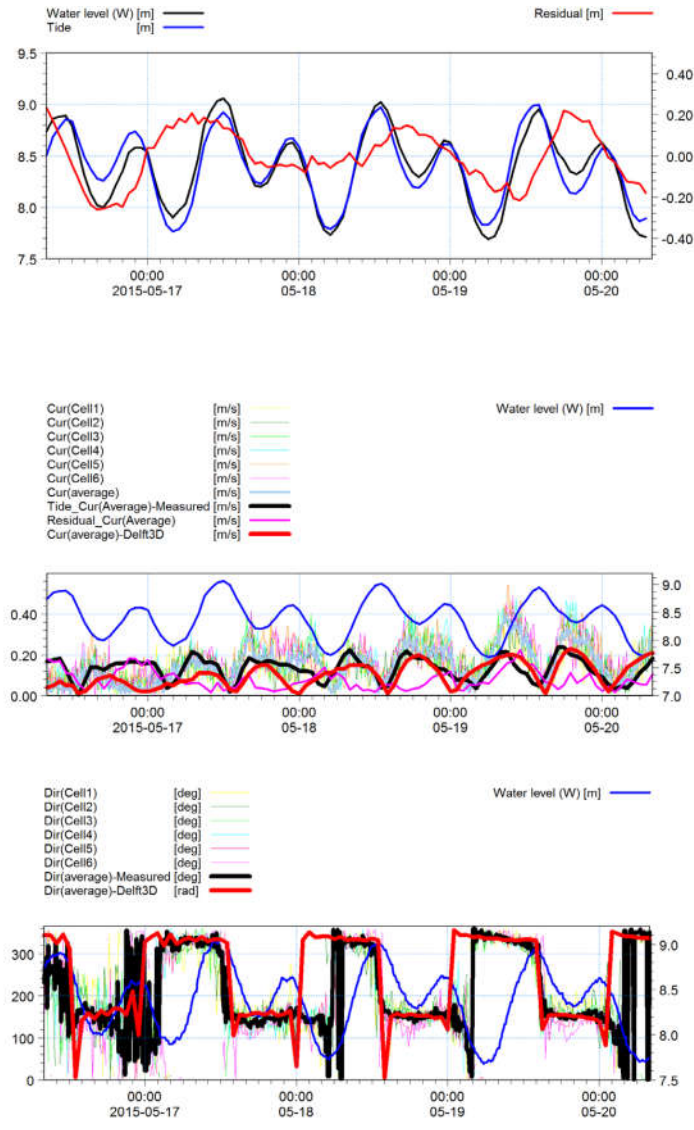


Figure 4: Actual water level variables measured and calculated at WL (in river) and AWAC system at sea

Calibration of the model: The simulation model is at the small time period with the measurement time for more better calibration model parameters for the study area, including flow, water level, flow. The simulated calculation results are quite good for the phase overlap measurement, which is relatively consistent with the actual measurement, allowing to evaluate the model set up with the adjusted set of parameters to be reliable.

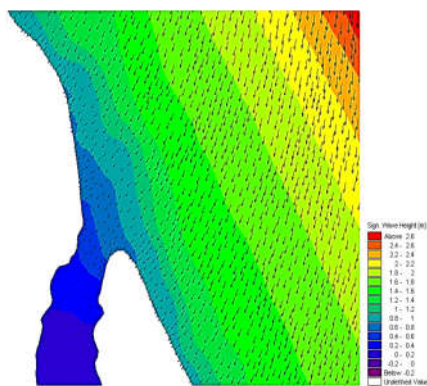
The hydrodynamic model has been calibrated for the period May 16 to May 20, 2015 using data collected at the AWAC station in the estuary. The initial model validation was carried out using the water level averaged over the river flow depth and wave measurements on the AWAC sensor. The simulation model coincides with the measurement time to serve to calibrate the best model parameters for the study area, including flow, water level. The simulation calculation results are quite good for measuring the phase overlap, which is relatively consistent with the actual measurement, allowing to evaluate that the model established with the adjusted set of parameters is reliable (see Figure 4). The Nash-Sutcliffe coefficient of the model compared with the surface water measurement data (x and y components) of the flow velocity is 0.96,

0.76 and 0.63, showing good agreement between the model and data [8].

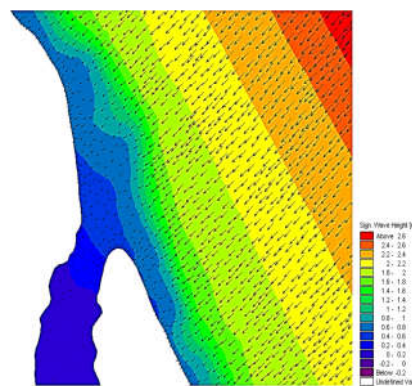
3. Results and discussion

On the basis of a calibrated model to investigate various influencing processes, such as tides, waves and river flows, the hydrodynamics and morpho - dynamics of the Nhat Le estuary were modeled and analyzed. Firstly, freshwater inflow and tidal influences were modeled to investigate the effects of tides on hydrodynamics regimes. Then, a complete hydrodynamic model of all factors (fresh water inflow, tides, winds and waves) was performed.

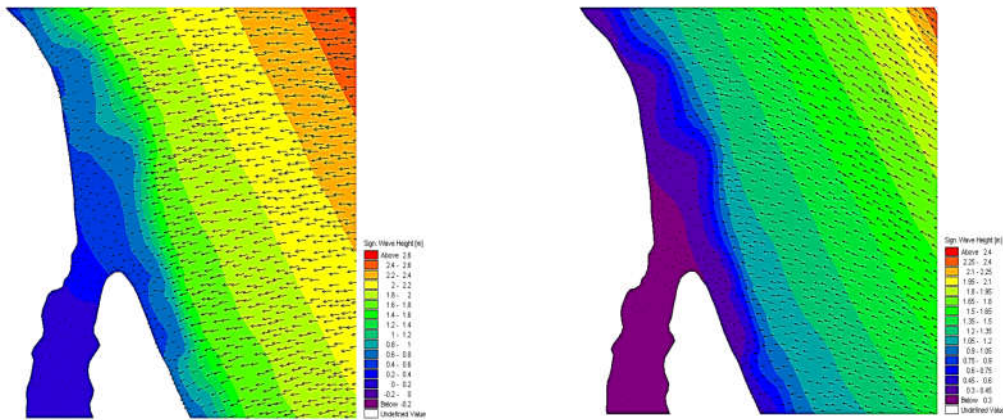
Wave characteristics: In the coastal zone of Quang Binh, wave has great significance for the process of accretion - erosion of the coast and estuaries compared to other types of other factors. In experience shown that studying waves in shallow coastal water for identifying coastal alluvial flows as well as determine the mechanism of accretion - erosion in coastal estuaries is indispensable. From these results, it can be seen that waves in deep - water areas are higher in the winter months and dominate from the east and north - northeast direction. In the summer months, the waves are much smaller and prevail from the south - west direction (see Figure 5).



North wave field



North - East wave field



East wave field

East - South wave field

Figure 5: Simulation of wave field in Nhat Le estuary area

Therefore, waves of the dominant eastern direction can be the main source of alongshore sediment transport in the estuary. Due to the action of waves of the dominant east direction, the net mass alongshore sediment transport is directed to the south - east - north - west, which lengthens the southern sandbar and forces the main channel of the river to turn north.

Through the calculation results of the wave characteristics, in the study area the wave breaking area is located at about 200 - 450 m from shore. Wave energy is concentrated in the winter months (from September to March of next year) accounting for 65.2 % in the deep-water zone, 77 % in the shallow water zone of the total annual wave volume. During the months of X, XI and XII, wave energy has the greatest value, when the processes of coastal erosion and sedimentation occur. Wave energy is lowest in months V, VI, VII and accretion activities mainly take place during this time. In the deep-water zone, the northward wave energy is the largest, followed by the NE and SE waves. In shallow water, large wave energy has a

direct influence on the estuary zone of the study area, which are the N and NE wave directions in the winter and the SE and N wave directions in the summer. Waves that generate the greatest energy have a height greater than 1.25 m. Although the frequency is not very large, they account for 63.6 % of the wave energy in deep water.

Wave flows: Wave flows in the breaking wave area are the results of interaction between wave height and coastal topography (see Figures 7, 8). Coastal wave currents play a very important role in the process of transporting sediments in the coastal zone. Wave effects is to transport a large amount of sediment along the shore and redistribute the sediment in the coastal area. It is also an important driving force causing sedimentation or erosion, destruction or formation of sandbars in the coastal zone.

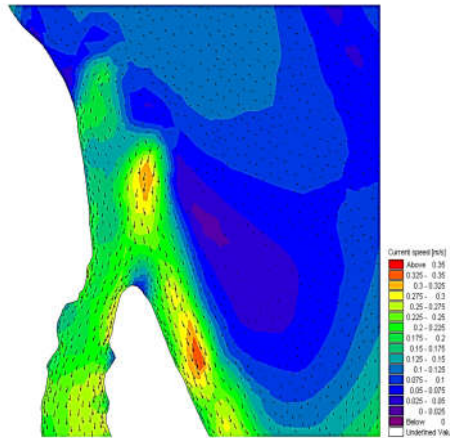


Figure 7: Simulation of the flow field under the effect of the northeast wave field

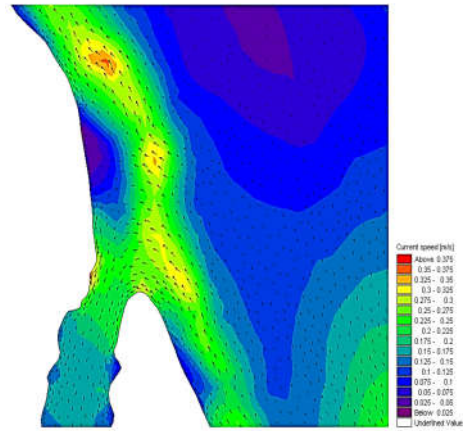


Figure 8: Simulation of the flow field under the effect of the southeast wave field

Tide regime with monsoon: Figure 9 shows the peak tidal velocities in three different situations: 1) tides only, 2) tides and northeastern waves during the winter monsoon season and 3) tides and southeastern waves during the summer monsoon season. Images of depth - averaged currents during tidal ebb current show high velocities in the tidal channel at the entrance to the estuary due to its narrowing from the lengthening of the southern sandbar. Thus, the model results show that tidal and river flows dominate in the main channel and in the inner estuarine zone. Especially, during river runoff floods, which often occur during the winter months and move the sediment towards the sea, then sea tidal currents will carry them to the southern coast. Wave - induced flows and alongshore currents prevail in the tidal zone and in the coastal area on both sides of the estuary. In the coastal zone away from the mouth of the estuary, wave flow is often driven by the interaction of waves and bathymetry. The strong impact of waves, changes the structure of the depth - averaged velocity, especially near the coast and

the sand bar due to the breaking wave in this area. In conditions of a combination of currents and waves, the magnitude of the flow increases significantly in the tidal channel and especially in shallow water. Coastal wave flows occur over most of the coastline and can reach strengths of 0.5 m/s. These flows, combined with tidal and river flows, create a stream that can reach a depth of 10 m at low tide.

Tidal current: During high tide, the tide flows from the South to the North, while at low tide, the current flows from the North to the South. Therefore, the sediment transport effects of tidal currents are usually small and somewhat offset in a tidal cycle. Tidal currents can be resonated or suppressed with wave and river currents depending on the tidal phase. In the breaking wave zones, the combined currents will increase during high tide and decrease during low tide in summer. In winter, the combined flow will decrease during high tide and increase during low tide. In the estuary area, in the dry season due to the weak river flow, there is no strong disturbance between tidal and river flows. In the rainy

season, due to the resonance of river flow and tidal current when the tide recedes, the resonant flow has a rather large velocity (>1.5 m/s). Therefore, tides and tidal currents only indirectly affect the shoreline through resonance with wave and river currents. However, if there is a resonance of adverse factors such as high tide, high waves and northeast monsoon, the impact of erosion and changes in the channel will be very large.

Sediment transport and bottom changes: Sediment transport plays an important role in coastal engineering in general and in the study of coastal developments in particular. Main problems related to coastal changes are the lack of sand and mud leading to coastal erosion; or the phenomenon of excess sediment causing sedimentation of estuaries, reducing flood drainage capacity, obstructing traffic, or navigating the port. Sediment transport in coastal areas is often classified into two separate forms: firstly, transport of sediment in the direction parallel to the shoreline, also known as longshore sediment transport; and transporting sediment in the direction perpendicular to the shoreline, also known as cross-shore sediment transport (see Figure 9).

In general, longshore sediment transport is the main cause of long - term shoreline evolution; in contrast, transverse sediment transport on the beach cross - section often causes short - term coastal changes. If the horizontal changes happen repeatedly for many years, it can also be the cause of long - term coastal erosion and accretion. In the study of coastal changes, the calculation of sediment transport in the coastal area is very important because the

sediment is the intermediate factor in the process of causing erosion or accretion in the coastal area. Knowing the amount of sediment transport in the coastal area, it is possible to predict the change of shoreline in natural conditions as well as evaluate the impact of construction works in the coastal area in the future.

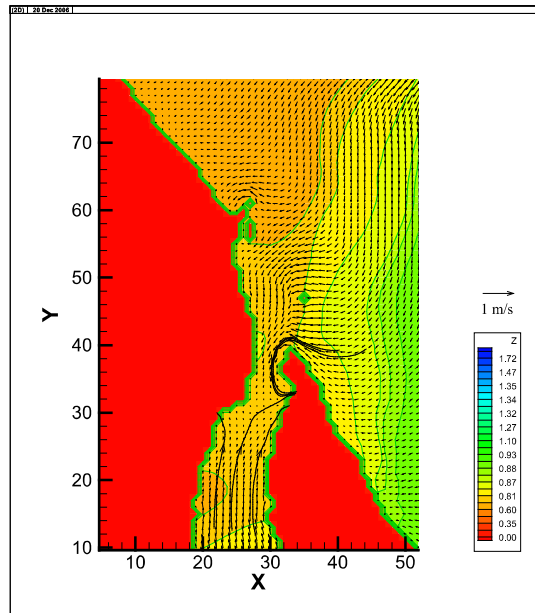


Figure 9: Simulation of preventing of the water flow directly affecting the bank causing erosion near Nhat Le estuary

In this study, the size of the sediment particles is set to be uniform - $d_3 = 0.03$ mm based on the data of bottom core samples analysis. The main parameters of the impact on sediment transport and morphological reactions were tides, tidal waves and river runoff. Modeling high - water river runoff shows that sediments move from the estuary to the tidal delta (Figure 10). Along shore wave and tidal currents redistribute these deposits, accumulating them along the coastline.

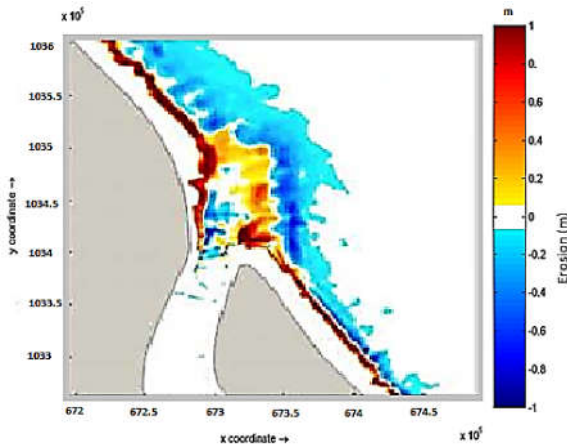


Figure 10: Erosion/sediment patches modeled for the September 2015 flood (right) and Google Earth image (left) for the same period

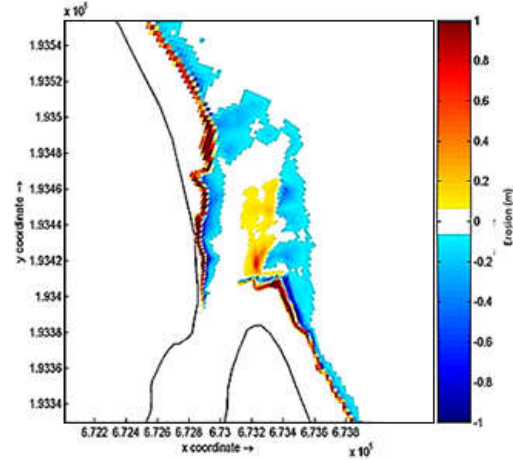


Figure 11: Erosion/sediment areas modeled during the 2015 dry season

During the low - water season, as a result of alongshore movement of sediments from the south, which is weakly interrupted by tides and river inflows, sediments continue to accumulate on the southern side of the tidal delta and at the end of the southern sand spit, which leads to the development of a sand spit northward (Figure 11).

According to the results calculated in Table 1, the total amount of annual longshore sediment transport through the calculated locations does not have a big difference, but main direction to

southward. The transportation of sediment only concentrates from September to March next year, accounting for over 90 % of the total transport volume of the whole year, the biggest shipping months are November and December. During the summer months, the amount of sediment transport is negligible. The wave causing the largest amount of sediment transport is the N and NE direction waves. The wave level causing the largest amount of sediment transport is the 3rd and 4th grade waves with wave height of 0.75 - 1.25 m.

Table 1. Total annual average amount of long-shore sediment transport (m³/year) in the coastal area of Nhat Le river mouth

Position	Q ⁺	Q ⁻	ΣQ
Section 1 - North Nhat Le river mouth	859 047	265 012	594 035
Section 2 - South Nhat Le river mouth	612 750	194376	418 374

Q⁺ - Sediment transport to the South; Q⁻ - Sediment transport to the North;

ΣQ - Total amount of sediment transport in the direction

The horizontal sedimentary flow is formed by the effect of wave pressure with the rock and soil of the shoreline. This is a direct and important impact on the process of accretion erosion of the coast and estuaries. The direction of the horizontal sediment flow during a wave action cycle is very complicated, especially in the estuary area. Depending on the wave

energy, the horizontal sediment flow has two transport directions from the coastal zone towards the underground bank and vice versa. The first direction causes erosion when the shoreline receives a large amount of energy and the second direction causes estuary sedimentation and shoreline accretion. If there are no storms and only wave effects are

considered, these two processes are balanced in a year.

Calculation results show that the largest sediment discharge is usually located in the breaking wave area. In the years without storm or tropical depression, due to the topography of the seabed, close to the sloping shore, there is not a big difference in the boundary of the winter and summer sediment transport zones in the study area. The amount of sediment brought to the underground bank by high waves in winter are deposited back by smaller waves in summer. Then part of the sediment is transferred from the south and the horizontal sediment flows from the south to the west. Therefore, the ability to dissipate sediment towards the underground bank in one year is not significant. In contrast, in years with major storms, the extent of the sediment transport zones in the storm (which coincides with winter) and the summer is very different. At the time, a part of the sediment brought to the sea by waves during the storm will be outside the range of the summer sediment transport zone, so it will not be returned to the coastline, leading to a shortage of sediment sources in the next time; as a result, the coastline is eroded.

The direct cause of erosion of Nhat Le coast is high wave pressure in thunderstorms, storms and northeast monsoon. Waves play a major role in causing shore erosion and turbulence of bottom sediments and transport along the shore and away from the shore. The results of the calculation of the sediment balance through the cross-sections of the Nhat Le river mouth (Tab. 1) show that the alluvial flow in the study area tends to prevail from north to south, with a total volume of 594,035 m³/year in close to the

estuary, the alluvial flow close to the bank has the opposite direction from south to north. Synthetic alluvial flow is diverged in the middle of moving sediment along the shore to the North and South East, erosion mainly occurs in the northeast monsoon season combined with weather disturbances. The boundary line erodes and erodes the bottom to a depth of 4 - 5 m. Outside the depth of 5 m is an area that tends to be accreted into sandbars below surface water.

The mechanism of alluvial transport causing shortage of sediment leading to coastal erosion from Nhat Le estuary to Quang Phu (Bau Tro) is shown as follows: longshore alluvial flow due to breaking waves is not large. The negative balance goes to the Southeast, causing a shortage of sediment of about 175,661 m³/year, causing serious bank erosion on the left bank of Nhat Le estuary and Quang Phu (Bau Tro) coast. The area where accretion occurs is concentrated mainly on the right bank of Nhat Le estuary.

4. Conclusion

This work presents the hydrodynamics and morpho - dynamics of the Nhat Le estuary based on the collected data and numerical simulations using Delft3D model. Seasonal variations in freshwater runoff and ocean waves in the tropical monsoon have an important influence on the behavior of estuary morphology. River sediments are carried into the tidal delta due to the dominant freshwater inflow and tidal currents. Outside the estuary, dominant ebb currents carry sediment to the south and south coast. The prevailing waves in winter and summer cause alongshore sediment flow in the southeast - northwest direction. During dry seasons, this alongshore sediment

transport is predominant, leading to sediment deposition on the southern side of the tidal delta and lengthening of the southern sand spit, which narrows the estuary entrance and alters the orientation of the main channel.

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