Human Impacts on Estuarine Erosion-Deposition in Southern Central Vietnam: Observation and Hydrodynamic Simulation

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Abstract: This paper aims to identify the causes and sources of erosion and deposition at small estuaries in southern central Vietnam under human intervention. The jetty built at the Tam Quan river mouth (Binh Dinh Province, Vietnam) serves as the base for the study. After its completion at the end of 2009, the hydrodynamic and erosion-deposition processes in the region have been significantly altered. Inside the estuary, the waves are not influenced, but the currents are increased during the ebb tide period and decreased during the flood tide timeframe. During the southwest monsoon, the jetty could cause an increase in the deposition process in both frequency and area, whereas the erosion process tends to narrow the area and increase the frequency on the north coast. In contrast, both deposition and erosion processes are increased on the southern coast. About 5859 m³ of sediments are deposited in the channel gate mainly by local sources. During the northeast monsoon, both deposition and erosion processes are located over a narrow area with frequency increased on the north coast, whereas the deposition process is narrowed with higher frequency on the southern coast. The total amount of sediment deposited at the estuary is 56,446 m³, of which 74.2% is from the onsite erosion material, 15.8% from the river and 10% from the longshore transportation. Generally, due to mainly erosion-deposition processes, sediment volume is accumulated during the northeast monsoon with amount 9.6 times more than that the southwest monsoon. The erosion-deposition processes are contributed to by poor practical management and local human activities inland and in the coastal regions, as well as the natural situation, resulting in serious impacts on society, the economy and the environment. Hence, the governance of the erosion-deposition processes and sediment load in small estuaries appear to contribute to the master plan for the local sustainable development of society and the economy.

Keywords: small estuarine; wave; current; sediment; erosion-deposition process; human intervention

1. Introduction

Estuaries are ununiformed waters, considerably disturbed by seawater and freshwater masses [1,2], as a result of the sea–land interaction presented by several hydrodynamic and biological processes [2–5]. Hence, estuaries are important in terms of ecological significance, as well as socio-economic development [4,6]. Due to the impact of natural hydrodynamic process, the estuarine area is often changed in the geomorphologic signature [3,6]. However, the river mouth succession takes place for a long time. For a
large river basin, this process can take place from a few decades to hundreds and/or thousands of years [4], whereas for a small estuary, development and changes in the river region may take place in a shorter time under the impact of human activities [7,8].

Estuaries are the regions vulnerable to erosion and deposition sediment [6,9]. Under the impact of natural processes, such as flooding and hydrodynamics with the high pressure of tropical storms and tropical depression and oceanography, the morphology and shoreline are changed, having a high impact on the coastal habitats [10], economic development, ship transportation and local living [11]. To limit these problems, people could launch marine/coastal construction to reduce hydrodynamic forces as well as to protect the coastline/beach. However, after construction in estuaries and coastal regions, the hydrodynamic regime is accordingly modified. In the case of a large river system, the construction along the river could reduce the volume of sediment discharge to estuaries, such as the dams in the Mekong River, reducing the sediment budgets by up to 74.1% in the Vietnamese Mekong Delta [12] and causing the change in the morphology of estuaries due to a lack of sediment materials [13]. In the case of a small river, the construction could bring benefits for coastal development, but also cause negative impacts on ecosystems and navigation in the adjacent regions of the construction [14,15].

Besides the large river systems (Red River, Mekong River), small rivers play an important role in the socio-economic development of Vietnam in general and particularly in the southern central coast. The southern central coasts cover a region from Da Nang Province (latitude of 16.21° N) to Ninh Thuan Province (latitude of 11.33 °N) (Figure 1). The river network in this region is complex, with every 20 km of coastline having a mouth or an estuary. These rivers are short and sharply sloping. Under the influence of manmade and natural disturbances, the river system is drastically changing. In the flooding period, the runoff tends to cause erosion in the coastline and seabed. Applications of hydrodynamic modeling in the studied field of erosion and sedimentation in estuaries have been carried out in recent years, but most targets are in the mega-river systems. A few studies have addressed the erosion and sedimentation process in the estuaries of small rivers in the southern central regions. About 90 eroded sites had been detected along the coastline of the South Central Region, representing 0.1–7.0 km of eroded coastline and an erosion rate of 0.43–80.0 m/year [16]. The eroded materials are moved out and/or deposited in the estuarine regions [17], causing changes in the morphological and topographical seabed and impacts on marine transportation [18]. The evidence indicated that marine construction in the coastal regions and estuaries could improve the living of standard for local people.

Tam Quan Mouth, a small river in the southern central regions of Vietnam, plays an important role in transportation, fishing and local living. After the jetty was built at the end of 2009, the deposition process at Tam Quan River mouth occurred strongly and caused transportation difficulty [19]. Changing the hydrodynamic regime between the southwest vs. northeast monsoons and supporting the effluent jetty could cause deposited sediments in the estuary and increase the sedimentation at the gate [20].

However, several crucial scientific issues remain and must be further examined. They include the sediment deposition in the Tam Quan Mouth and small estuaries, the causes of deposition and the sources of the material sediments, especially under the disturbances of humans and implemented governance of the local and national governments. This paper seeks answers to the raised issues and questions. The detailed reasons and mechanisms of the changing seabed under anthropogenic impacts will be presented. Based on the balance of the sediment budget, the changes in the seabed can be predicted and indicated with the pathway of sediment movement. These changes could influence the living standard of local people and contribute to reducing the inequalities among communities in river catchments, included in Sustainable Development Goal 10. The results are expected to quantify the assessment and analysis of the spatial changes in the erosion and sedimentation processes in the small estuary, and determine the causes of the morpho- and sediment-dynamic changes under a combination of natural and an-
thropicogenic factors in sloping and small estuaries in the central regions of Vietnam.

2. Materials and Methods

2.1. Study Area

According to decision No. 1672/QĐ-TTg of the Prime Minister of Vietnam [21], the town of Hoai Nhon is oriented to develop into a central urban sub-region of Northern Binh Dinh Province [22]. This town will be developed to become a center of marine commerce, services and economic development [22,23]. In particular, the seaport systems will be invested in and upgraded based on the local estuaries. However, the features of rivers in the central coastal region, in general, and Binh Dinh, in particular, are short and sloping [16,24]. The hydrological regime of these rivers seriously changes with the tropical monsoon climate [16]. During the dry season—mainly from May to September—and under the influence of the southwest monsoon, most rivers lack water sources from the upstream, so that the sediment sources significantly decrease, whereas in the rainy season, which usually overlaps with the flood season and the northeast monsoon, the river is flooding and combined with a large sediment source of about 76% of sediment loading from September to December [17]. Consequently, the current status and morphological characteristics of estuaries are affected. This drastic change causes erosion and accretion of estuaries, thereby making the river bed shadowed and narrow. As a result, it has a very serious impact on the access of existing ships as well as the future direction of the seaport system development. To control these estuaries, the local government carried out artificial construction in estuaries. Nevertheless, this caused negative changes due to the impact of natural conditions from the inland, the sea and climate changes coupled with extreme weather.

2.2. Materials

The topographic and bathymetric maps in the study regions were digitized with the sea charts “From Dai mouth to Mya mouth” and “From Mya Mouth to Quy Nhon bay” (scale 1:200,000; published by Vietnam People’s Navy in 2011) and the sea chart “Bathymetry map from Binh Son (Quang Ngai Province) to Quy Nhon (Binh Dinh Province)” (in the depth of 0–60 m, scale 1:100,000; published in 2014). The bathymetric map resulted from the project “To investigate geological characteristics, geodynamics, mineral geology, environmental geology and to predict geological hazards for the coast of Thua Thien Hue-Binh Dinh (0–60 m of water depth), scale 1:100,000” (by Marine Geology and Mineral Resources Center, Vietnam).

In addition, the bathymetric data in Tam Quan River and adjacent regions by the surveys during the northeast monsoon (in December 2014) and the southwest monsoon (in May 2015) were collected through the project “Assessing influences of constructions on the hydro-lithodynamic regime and morpho-structure of river mouths in the southern center of Vietnam and proposing measures in response to consequences” (code: VAST05-04/14-15). These data were used to support the validation and calibration of seawater level at the W station and morphological seabed at the GH and KI transects in the model (Figure 1). The sediment grain size in regions of the Tam Quan river mouth was collected and measured.

Wind field data were collected in the timeframe from 1994 to 2015 at the Ly Son Station (a Vietnamese island located about 100 km northward of Tam Quan Estuary).
Figure 1. The depth and mesh: (a) extended calculation region and (b) study area. The W station was the place to collect data for seawater level calibration, GH and IK were the transects to collect data for calibration of bathymetric value and polygon ABCED was used to estimate the sediment transportation volume.
2.3. Data Collection

Water levels were measured every 30 min by metric rule with accuracy of 1 cm at the W station (Figure 1b) and four stations at sections I and II (Figure 1b). These data were used to correct the bathymetric data for the morphological sea/riverbed, and validate and calibrate the hydrodynamic models. Data of water level and river discharge at four stations in sections I and II were used for training, whereas the water level at the W station was used for validation.

A principal system of determining sea/riverbed depth was applied for the collection of bathymetric data by DGPS and an echo sounder (Figure 2). These data were collected in the surveys during the northeast monsoon (in December 2014) and the southwest monsoon (in May 2015) according to the track lines in the study map (Figure 3). In total, 35,192 points of morphological data were collected, in which about 15,000 points were distributed in the river/channel and mouth, called set “A”. About 75% of dataset “A” were used for training, whereas the other 25% localized around the transects GH and KI were used for validation.

At the sections I and II, water current, volume discharge and water level were measured. The data were used to calculate input data and estimate the volume of runoff.

2.4. Modeling

Simulation of hydrodynamic and sediment transport was conducted by the DHI software, the MIKE 21 flow model FM with Hydrodynamic and Sand transport modules, whereas the wave parameters were calculated from Spectral Wave FM [25] in the cases with and without a jetty. The region of concern was extended from the latitude 15°13′ N to the north, from the latitude 13°56′ N to the south, and from the longitude 109°50′ E to offshore. A mesh with 7333 triangular elements was established for that region (Figure 1a). For the offshore areas and coastal areas with simple shorelines, the mesh elements were roughened with the size of element ranging from 100 m to 10,000 m. In the Tam Quan river mouth and areas with complex shorelines, the mesh elements were smoothed with the size of 10–110 m (Figure 1b). Due to the slope of the seabed, the estuary/mouth and offshore boundary are just about 3 km, while the river mouth width is about 150 m.

**Figure 2.** The principal system of determining sea/riverbed depth by dynamic DGPS measurement. HA is the base station antenna height compared to the landmark, measured by rulers with accuracy of approximately 5 mm. HB is the antenna height of the station (Rover) compared to Ellipsoid’s face. F is the height of the station’s antenna relative to the bottom surface of the sensor at the position of the boat, measured by a ruler with accuracy on the order of cm. D is the depth of the bottom, measured by an echo sounder. HA is the height of the landmark compared to the reference ellipsoid. HB is the height of the sea/river bed. W station is the water level reference station.
Figure 3. Track lines for collection of bathymetric data.

The modeling conditions at the offshore boundaries (I-II, II-III and III-IV in Figure 1a) applied for the Hydrodynamic module (MIKE 21 FM) were the water level fluctuations derived from the Toolbox “Tide Prediction of Heights”. The data of liquid boundaries in the rivers at section I and section II (Figure 1b) were river discharges measured during the southwest monsoon (December 2014) and the northeast monsoon (May 2015).

In the Spectral Wave FM module, the offshore boundaries were defined as lateral boundaries and the closed boundaries were assumed in the river sections. Because the suspended sediment concentration in rivers was negligible, even in the rainy season (December 2014), only the non-cohesive bottom sediment transport was calculated with a particle having a median grain diameter (d50) of 0.25 mm.

The model calibration was performed by changing Manning coefficients (Ms) in the region as specified: (1) at the sea, the areas with depth > 5 m, Ms are about 48–51 m^{1/3} s^{-1}, and in the areas with the depth ≤ 5 m, Ms are around 35–40 m^{1/3} s^{-1}; (2) in the rivers and the channel, Ms = 20 m^{1/3} s^{-1}. To calibrate the stability of the numerical scheme, CFL (Courant–Friedrich–Levy) and Nash–Sutcliffe efficiency (NSE) were used. In MIKE 21 FM, the CFL number is less than 1 for all modules (CFL coefficient was taken to be 0.8 while setting up the models; CFL = 0.8). The calculation of NSE follows the formula:

\[
NSE = 1 - \frac{\sum_{i=1}^{n} (Y_{i}^{obs} - Y_{i}^{sim})^2}{\sum_{i=1}^{n} (Y_{i}^{obs} - Y_{mean})^2}
\]

where \(Y_{i}^{obs}\) is the \(i\)th observed value, \(Y_{i}^{sim}\) is the \(i\)th simulated value, \(Y_{mean}\) is the mean of observed data and \(n\) is the total number of observations.

Determination of the origin of materials causing deposition and erosion in regions of Tam Quan river mouth was carried out as follows:
Method 1. Based-pyramid balance of sediment budget: Calculate the volume of deposition and erosion sediments based on the simulation results of the bottom changes (Figure 4).

![Figure 4](image)

Figure 4. Sketch of calculating bottom changes.

Method 2. Based cross section balance of sediment budget: Calculating the amount of sediment moving through the sections of study observation based on the volumetric transport rate to determine the origin of sediments—\( V_{sec} \) [m³] is the total volumetric transport rate of sediments across the section \([m^3 \cdot m^{-1} \cdot s^{-1}] \times \) section width \([m] \times \) time \([s] \).

The above methods were applied to identify the origin of sediments that cause the deposition-erosion processes in the polygon. The volumetric transport rate of the sediments was calculated through the AB, CB and DE sections (Figure 1b).

2.5. Data Analysis

Mapping observation data and spatial analysis was conducted with the software MapInfo version 17. Hydrodynamic and sediment transport modeling was applied by MIKE 21. All the data applied were through a one-way ANOVA test with \( p = 0.05 \). The parameterization settings in the algorithms for the hydrodynamic and sediment transportation model were accepted with CFL = 0.8 and NSE > 0.7.

3. Results

3.1. Observation Data and Calibration of Model

The results of river discharge flow in the sections I and II were indicated in Figures 5 and 6, respectively. During the northeast monsoon, the flooding current of the river runoff was mainly contributed to at the almost observed time by a large water volume during the rainy season. The total runoff volume was positive, as shown in Figures 5a and 6a. However, in the southwest monsoon, the daily river flow was changed in direction between runoff and run-in, depending on tidal regimes (\( p = 0.05 \)) (Figures 5b and 6b).

As the results of changes in the water current in the Tam Quan mouth, the morphology changes were displayed in Figure 7. The erosion processes were significantly localized at the entry of the gate, whereas the deposition significantly occurred inside the channel and outside the gate (\( p = 0.05 \)).
Figure 5. Runoff observation in section I, (a) northeast monsoon and (b) southwest monsoon.

Figure 6. Runoff observation in section II, (a) northeast monsoon and (b) southwest monsoon.
Figure 7. Status of erosion/deposition in the Tam Quan during the period of December 2014 and May 2015 ($p = 0.05$).

By the observation of the water level and bathymetric data to calibrate the hydrodynamic model and evaluate the reliability of the calculated results, the water level fluctuations at the W station (Figure 8a) and the bed level changes in the KI section (Figure 8b) were compared. The Nash–Sutcliffe efficiency (NSE) coefficient for the case of the water level fluctuations was 0.99 (very good) (Figure 8a), and 0.77 (good) for the bed level changes (Figure 8b).
Figure 8. Comparison of measurement and calculation results, (a) calibration of seawater level at W station from 8 AM 21 May to 0 AM 23 May 2015 with NSE 0.99 (very good), (b) calibration of sea/river bed along the KI section on 22 May 2015 with NSE 0.77 (good).

3.2. Hydrodynamic System

The currents in the river mouth region were a synthesis of river-out flows, tidal currents and wave-generated currents (Figures 9–14). The tidal currents were quite stable and cyclic, whereas the river-out flows changed seasonally. The wave-generated currents mainly existed near the coast, changed quickly and depended on the winds of the region. During the southwest monsoon season and dry season, from May to September, the wind direction was mainly in the SE–S (southeast–south) arc with a frequency of 30.4%, and in the SE direction with a frequency of 13.4%. During the northeast monsoon and rainy season, from October to March, the wind direction was in the NW–NE (northwest–northeast) arc with a frequency of 45.7%, and in the NE and NW directions with frequencies of 10.9% and 12.1%, respectively. The wave-generated currents are always in the direction from the Truong Xuan headland into the river mouth during both the southwest and northeast monsoons (Figures 9 and 13). The sediment sources causing the erosion-deposition processes were generated by the stimulation of hydrodynamic processes and the sediment transport that significantly occurred during the medium period (monsoon season).
Figure 9. Waves during the southwest monsoon (a) without jetty and (b) with jetty.

Figure 10. Wave during the northeast monsoon (a) without jetty and (b) with jetty.
Figure 11. Currents at the rising tide during the southwest monsoon (a) without jetty and (b) with jetty.
Figure 12. Currents at the ebb tide during the southwest monsoon (a) without jetty and (b) with jetty.
Figure 13. Currents at the strong flood tide during the northeast monsoon (a) without jetty and (b) with jetty.
Figure 14. Composite currents at the strongly ebb tide during the northeast monsoon (a) without jetty and (b) with jetty.

3.2.1. Waves

The scenario results of the southwest and northeast monsoons in the cases with and without a jetty (Table 1 and Figures 9 and 10) show the same pattern of wave systems, but have different patterns in the mouth/channel over small regions. The waves were significantly reduced, with a maximum height of 0.2 m in the channel or river. After a jetty was built, waves in the channel area were completely calm (Figures 9b and 10b).

Table 1. Scenario of wave system in the cases with and without a jetty. (Note: E, east; W, west; N, north; S, south.)

| Figure | Factor | Southwest Monsoon | Northeast Monsoon |
|--------|--------|-------------------|-------------------|
| Wind condition | Direction | S–SE | N-NE |
| | Velocity (m s−1) [range(mean)] | 2–8 (4.5) | 6–14 (10.6) |
3.2.2. Current Regimes

The scenario results of current regimes during the southwest and northeast monsoons for the cases with and without a jetty are indicated in Table 2 and Figures 11–14. The current is unchanged in the offshore regions in the cases with and without a jetty, but there was big difference in the northern and southern coastal waters and mouth/channel (Table 2). In the case with a jetty, the current velocity in the channel was increased, and the current regimes were more complex in the southern waters with more eddy than the case without a jetty.

Table 2. Scenario of current regimes in the cases with and without a jetty (E, east; W, west; N, north; S, south).

| Areas              | Factor                      | Southwest Monsoon | Northeast Monsoon |
|--------------------|-----------------------------|-------------------|-------------------|
|                    | Without Jetty | With Jetty       | Without Jetty | With Jetty       |
| North coast        |               |                  |                  |
| Direction          | S             | S                | S                | S                |
| Current velocity (m s⁻¹) | 0.05–0.53       | 0.05–0.62        | 0.25–1.48       | 0.25–1.48       |
| South coast        |               |                  |                  |
| Current velocity (m s⁻¹) | Mean: 0.10       | Mean: 0.10       | Mean: 0.23       | Mean: 0.19       |
| Direction          | NW            | W and NW         | E, Clockwise     | S                |
| River mouth/channel| Current velocity (m s⁻¹) | 0.10–0.38       | 0.12–0.32        | Mean: 0.16       | Mean: 0.16       |

3.3. The Impact of the Jetty on the Movement of the Bottom Sediments

Scenario results of morphological changes during the three months of the southwest and northeast monsoons in the cases with and without a jetty are shown in Figures 15 and 16. During the southwest monsoon (Figure 15), the erosion-deposition processes occurred less slightly than during the northeast monsoon in both cases. In the case with a jetty, the deposited regions were mainly at the gate and adjacent waters. During the southwest monsoon, in the case with a jetty, the erosion-deposition processes occurred along the jetty sides. The regions of 11,850 m² in the channel nearby the jetty head had gradually ended with shallowing and connected with the northern coastline. The sediment sources of 580 m³ were deposited on the channel region of 18,470 m². The erosion occurred in the narrowest region of the channel and along the northern jetty side. The eroded regions around the jetty head were mainly impacted by the waves.
Figure 15. Erosion-deposition distribution due to the combined effects of waves and currents from 1 May to 31 August 2015 during the northeast monsoon, (a) without jetty and (b) with jetty.

During the southwest monsoon, erosion-deposition processes occurred dramatically in the mouth and/or channel and adjacent regions (Figure 16). In the case without a jetty, the deposition covered almost all the regions of the mouth. In contrast, in the case with a jetty, almost these regions were converted to eroded regions, and the deposited regions were shifted to the entry of the gate and adjacent regions. The deposition with height mainly from 0.01 to 0.5 m approximately occupied 71% of the area of concern and 51% in terms of sediment volume. The deposition height could reach the maximum value of over 2.0 m (Figure 16b).

Figure 16. Deposition-erosion distribution due to the combined effects of waves and currents from 1 November 2014 to 31 March 2015 during the northeast monsoon (a) without jetty and (b) with jetty.

4. Discussions

4.1. Sinks and Sources of Sediment

The morphological changes in the seabed are the result of the combined impacts of hydrodynamic processes (waves and currents) with the component sediment materials.
Waves play a major role in stirring up sediments from the seabed, creating wave-generated currents, which transport sediments [27,28]. The asymmetry of velocities under the crest and trough of waves could also move the sediments [15,26]. The currents stir up and transport the sediments, which are largely moved following the direction of the current [29]. As the waves and currents interact with each other, their interaction cannot be characterized only by the linear sum of their separate impacts [30]. Instead, it is seen in at least three ways [29]: (1) change in the phase speed and wavelength of the wave by the current, resulting in the refraction of the wave; (2) interaction of the wave and current in boundary layers, resulting in the enhancement of both steady and oscillatory components of the bed shear-stress; and (3) creation of currents by the waves, including longshore currents, undertow and mass transport currents. To estimate the changes in the morphological seabed, the sediment transport rate was used for the polygon of ABCD. The sediment transport rate is defined as the mass/volume of sediment materials passing a flow-transverse cross section in unit time [31].

In the southwest monsoon season, while applying Method 2—Based cross section balance of sediment budget—to estimate the eroded and deposited sediments in the polygon ABCED, the behavior of sediment transportation was presented. At the section AB of 350 m in length, in the first 20 m of the section from the Truong Xuan headland, the sediment transport rate was negative (−), which means the sediment movement to the west with a maximum rate of \(-8.2 \times 10^{-7}\) m\(^3\) s\(^{-1}\) and total sediment of 61.5 m\(^3\) in volume passing the first 20 m section. In the next 90 m of the section, the rate was positive (+), meaning that the sediments moving out the channel reached a volume of 12.5 m\(^3\); in the rest of the 200 m section, the sediments move into the polygon by a volume of about 21 m\(^3\). Thus, the net sediments transported into the polygon through this section were estimated at about 70 m\(^3\) in volume (Figure 17).

At the section DE of 180 m in length, in the first of 30 m section from the 10 m northern coastline, the sediment transport rate was negative (−), indicating that the sediments moving to the west or flowing into the river were about the same as the first part of the section AB. In the remaining sections, the sediment transport rate was positive (+), meaning that the sediments move to the east from the river to the polygon. The net sediment transportation, originating from rivers, was about 130 m\(^3\) in volume (Figure 17). At the section CB of 550 m in length, the sediment transport rate was positive (+), inferring that sediments move to the north (into the polygon) with net sediments of 384 m\(^3\) (Figure 17). In total, the volume of sediments that moved into the polygon reached 584 m\(^3\), approximately 4.73 m\(^3\) day\(^{-1}\).

While applying Method 1—Based-pyramid balance of sediment budget—to estimate the sediment rate, the results indicate that about 5859 m\(^3\) of sediments were deposited and 6234 m\(^3\) of sediments were eroded in the ABCED polygon. The sediment volume calculated by Method 2 was about 5859 m\(^3\) completely deposited inside the polygon. The sediment volume calculated by Method 1 was also about 5859 m\(^3\) deposited completely in the polygon. Hence, still, 374 m\(^3\) of eroded sediments in the polygon were not moved out of the polygon. However, the erosion-deposition calculation was only applicable for the areas where the bottom level change has an absolute value ≥ 0.005 m. Therefore, 374 m\(^3\) of eroded sediments would be distributed on the regions with absolute bottom change < 0.005 m due to the calculation error of Method 1. Thus, about 5859 m\(^3\) of sediments were deposited with a balance as follows: sediments from the east (mainly coming from the north) accounted for 1.2%, 2.2% from the river, 6.6% from the south and the local sources mainly about 90%.
Figure 17. Sediment transport rate (from 1 May to 31 August 2015) through sections AB, DE and BC.

In the northeast monsoon period, the sediment transport rate of sections of the polygon ABCED is indicated in Figure 18.

At the section AB, the sediments that tend to move into the polygon with net transport into the polygon were 5625 m$^3$, and 91.7% of the sediments passed through the first 50 m of the section and up to 96.5% of the sediments passed through only 100 m of the section from Truong Xuan headland (Figure 18). At the section DE, the sediments always came from the river with net volume of 8923 m$^3$ (Figure 18). At the section CB, in the first of 55 m section from the jetty head, the volume of sediments moving into the polygon was about 494 m$^3$. In the rest of the section, the sediments that came out were with a volume of about 513 m$^3$. Therefore, the net sediment volume lost for the polygon was 18 m$^3$ (Figure 18). In total, during the northeast monsoon, the total volume of the sediments (calculated by Method 2) moving into the polygon was at least 14,534 m$^3$.

By using Method 1, the volume balance of erosion-deposition processes was estimated as the deposition by 56,446 m$^3$ and the erosion by 38,057 m$^3$. Thus, the net volume was 18,389 m$^3$. The total volume of sediments moving into the polygon through the sections was accumulated in the deposition regions. The sediment volume remained at 3885 m$^3$, deposited in the polygon with absolute value <0.01 m.

Generally, in this study, the deposition sediment volume during the northeast monsoon was 9.6 times more than that during the southwest monsoon. The balance of sediment sources was contributed to from the east by 10%, from the river by 15.8% and from localized regions by 74.2%. Ahmed et al. [17] also found that the annual total sediment loading from river catchment was about 13,954 tonnes, in which 76.73% of sediment volume was distributed during the flood season and the northeast monsoon, 3.3 times greater than that of the southwest monsoon. These comparisons indicate that more sources contributed to deposition sediment, particularly after the construction of a jetty.
The sources of sediment loading at the gate entry were from runoff water, inland materials, coastal erosion and offshore materials at the Tam Quan estuary. As a result, the channel area was the place with the most fluctuations [20]. Sediment transport depends on the flow field, which is mainly influenced by the waves and tides [17,20]. In mega-rivers, such as the Mekong River, sources of sediment were from inland, offshore and erosion materials [8]. This indicates that anthropogenic impacts—based on construction in the small estuaries—could be caused by an increase in the erosion-deposition processes. As a result, the morphologic river bed can be modified over time. Thus, it is necessary to have a master plan for implementation of the changes in the situation and morphology of the river mouth.

Figure 18. Sediment transport rate of (from 1 November 2014 to 31 March 2015) through sections AB, DE and BC.

4.2. Cause of Erosion-Deposition in Small Estuaries and Their Impacts on Socio-Economic Development

Estuaries play an important role in socio-economic development as well as in the protection of ecosystems. However, under impacts of human activities, estuarine ecosystems have been changed in both environmental and ecological aspects as well as in their morphology. Due to natural and anthropogenic processes, erosion-deposition has caused changes in the coastline and morphological seabed. In the case of the Tam Quan
estuaries, the erosion-deposition processes have occurred strongly and caused transportation difficulty [19].

Under impacts of the hydrodynamic process, several opinions supported the causes and material sources for the changes in the morphological seabed in the estuaries. In the hydrodynamic regime, the changing direction of nearshore current in the waters in front of the mouth could generate a local clockwise eddy that causes an instigating sedimentation deposition. As the southeast and east waves dominated during the southwest monsoon, they could generate a natural backwater region at the Truong Xuan headland. Then, the sediment materials might be accumulated on the inward wave side of the breakwater to form the arch coastline, and were redistributed at the gate and estuary. In addition, the northeast and east waves during the northeast monsoon season could transfer sediments from the north to the south and then the sediment is redistributed over wide areas out of the estuary [20]. Therefore, the provincial government invested in construction in estuaries to control the impacts of natural processes, such as flooding, deposition and erosion. However, the jetty caused deposed sediments in the estuary, increased the sedimentation at the gate and formed bars there [20].

After the jetty was built, the capacity of marine transportation was improved. However, during the southwest monsoon, due to low river discharge, the sediment materials are deposed inside and outside of the Tam Quan mouth. Especially, in the case with the jetty, the sediments could be accumulated more inside the channel. They could form the sand/alluvial banks, causing difficulty to transportation for boats to get in and out of the channel.

In contrast, the seabed in the southern onshore water of the Tam Quan estuary was often eroded seriously during the northeast monsoon with high waves and rising seawater levels. As a result, a fishing village was smashed and the mouth was strongly shadowed. Built jetty in the Tam Quan estuary helps reduce the seabed erosion and shoreline changes, but it causes an increasing deposition in the gate. As a result, reducing sediment fluxes towards the south waters leads to serious erosions of southern shoreline.

Furthermore, the erosion processes could become serious problems due to the exploitation of sand/mud and dredging of the ship-way in the Tam Quan estuary. Although the dredging volume of about 60 thousand m$^3$ was out of the estuary (Figure 19), sedimentation continues to contribute here, especially during the southwest monsoon. The deposition process would be increased after 2010 and the dredging process was in the southern Truong Xuan cape. Sediment fluxes from the North were moved through the Truong Xuan cape by the longshore current and trapped in the estuary area. Sediment load from the river and the eroded sediment out of the channel and adjacent regions were the deposition sources.

![Figure 19. Dredging activities for ship-ways in the Tam Quan estuary in 2018. Photo: Pham Ba Trung.](image)
sediment loading with higher intensity in flooding season, current and hydrodynamic regimes and waves and construction in the mouth; construction mainly contributed to the deposition of sediment at the gate of the mouth. The results of [20] agree with our findings of erosion being more intensive during the northeast monsoon due to load more flooding [17,20], whereas deposition processes were caused by the waves at the gate of Tam Quan’s mouth. Thus, the erosion-deposition processes in estuaries were results of land management in coastal and marine regions. The poor practical management led to an increase in the processes. Consequently, they cause serious impacts on socio-economic development and environmental conditions. Changes in these processes modified the sediment load in estuaries [32,33], disturbing the structure and functions of ecosystems [33,34] and causing negative impacts on ship-moving and navigation to access the ports. Increasing deposition and sediment load at the estuaries could result in improved water quality in the rivers, and modified the morphological riverbed. In contrast, the erosion could increase the suspended sediment concentration [35] and supply more nutrients to the aquatic systems, leading to water eutrophication and disturbance in the delicate aquatic ecosystems [36]. Hence, to reduce the impacts of humans and marine construction on the Tam Quan mouth and in the small estuaries in the south central regions, a master plan for sustainable development should be proposed for the governance of the erosion-deposition processes.

5. Conclusions

In general, the natural processes and anthropogenic impacts were considered as the main causes of the erosion-deposition processes in small estuaries in the southern central regions of Vietnam. For short and sloping rivers, marine construction in the estuaries can be helpful to control the erosion-deposition processes in order to improve the living standard of the local people and reduce the inequalities of human settlement in the river catchment. However, in the case of the Tam Quan mouth, representing the estuaries in the south central regions, a jetty can reduce the sediment deposition inside the channel and increase the sediment accumulation in the channel gate. The erosion-deposition processes mainly occurred during the northeast monsoon with the sediment volume accumulating 9.6 times more than that of the southwest monsoon. When the jetty was built in the Tam Quan mouth, the sediment deposition volume was increased more at the gate and in the adjacent waters. During the northeast monsoon, 56,442 m³ of sediment was deposited in regions of 129,405 m², whereas during the southwest monsoon, 5608 m³ of sediment was deposited in areas of 105,479 m². The causes of erosion-deposition processes were the factors of river/inland and ocean materials, current and hydrodynamic regimes, waves and construction in the mouth—construction represented the main contribution to the deposition of sediment at the gate of the mouth. Changing the mouth morphology with a jetty may cause variations in the current velocities of the waters, leading to the erosion-deposition of the coarse and fine sediments at the entry of the channel. However, the details of material transportation are beyond the scope of the current study and can be further studied in future work. The erosion-deposition processes were related to human activities, poor practical management in the inland and coastal regions and natural processes, all of which cause serious impacts on socio-economic development and environmental conditions. Therefore, the governance of the erosion-deposition processes as well as sediment load in small estuaries should be considered for the local sustainable development of society and the economy.

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