JOURNAL OF
HYDRO-METEOROLOGY

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Research Article

Application of 2D hydro-dynamic model to simulate the suspended sediment on the Tien river, Cao Lanh district, Dong Thap province

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Received: 10 June 2023; Accepted: 20 July 2023; Published: 25 September 2023

Abstract: This study was carried out to analyze and evaluate the change in the amount of suspended sediment on the Tien River in the Mekong Delta. Evaluating the sediment transport regime is a very important task to effectively serve the assessment of the level of evolution (erosion/accumulation) on the riverbed. This study applied the Mike 21FM hydrodynamic model to simulate the sediment transport regime on the section flowing through Cao Lanh district, Dong Thap province - where the erosion process is very complicated recently. The simulation results show that the largest number of displaced sediments appears on the right bank, the maximum amount of sludge transported ranges from 0.91 kg/m^3 to 2.7 kg/m^3. During the simulation period, the total amount of sediment that has moved downstream is about -218.7×10^6 m^3, the depth is -233 cm, the average rate of erosion is -77.6 cm/year, where the deepest erosion can be up to -10.0 m.

Key words: Suspended sediment; Sediment transport; River bottom evolution; Mike 21FM model.

1. Introduction

The phenomena of sedimentation and erosion are a natural process and occur continuously in most of the rivers on Earth. However, the process of sedimentation-erosion, especially riverbank erosion, becomes a concern when it causes great damage to land, property and people living along the riverbanks. In large rivers, scientists focus on the landslide process in the interaction between the country that occurs frequently over a long period of time [1–5]. Scientific studies around the world have studied the landslide process in different approaches and methods such as: (i) Approaching river geomorphology is the study of river morphological changes over time and space. These changes can be about: size, shape, river morphology [1–2, 6]; (ii) Hydrolith approach to river dynamics is to analyze the mechanisms of landslides, sediment transport and sedimentation due to river flows, from which to develop simulation methods, to calculate riverbed changes [7–8].

The situation of research on riverbed changes in the country and internationally is popularly carried out according to the methods in basic research such as: analysis method of measured data [9], physical modeling method [10], empirical formula method [11–13] or mathematical modeling method [14–17].

Dong Thap province is located in the southwestern region of Vietnam and is one of the important cities in the Mekong Delta with area of about 3.376 km². Dong Thap province borders Cambodia and is divided into 12 districts and Cao Lanh city is the administrative center, has a favorable geographical position, bordering Tien river and Hau river - two important rivers of the region [18–19]. The Tien River section flowing through Dong Thap province has a length of about 120 km, the river width varies from 450 m (An Long, Tam Nong) to 2,200 m (the beginning of Long Khanh and Hong Ngu district); Average depth from 10÷15 m. In recent years, changes in the banks of the Tien River, the section flowing through Dong Thap province have been quite complicated; the general trend is to increase the scale and extent. In addition to the main natural causes (flow dynamics, shoreline geology), socio-economic development activities also significantly affect the riverbank changes, typically sand mining along the riverbank in the locality [20]. Therefore, the study and assessment of sediment transport in the study area is necessary, making an important contribution to the management of water resources, environmental protection, and sustainable development of the Tien River area.

Actual data on measuring sediment content shows that the value of sediment content is not high, but due to the large amount of runoff, the total annual amount of suspended alluvium of the Tien and Hau rivers through two cross-sections at Tan Chau and Chau Doc stations is relatively large. Due to the flow 4-5 times greater than that of the Hau River and the higher silt content, the total amount of alluvium from the Tien River through the Tan Chau cross-section in the same periods is many times larger than that of the Hau River through the Chau Doc section. In the period 2009-2020, the total amount of sediment in the Tien and Hau rivers has the same rate of decline in proportion to the decrease in sediment content [21].

Commonly used methods to represent changes in river morphology as well as sediment transport under human impacts, hydro-hydraulic regimes, climate change and sea level rise by means of mathematical modeling, physical modeling, remote sensing technology and GIS [1–2]. In this study, software package for 2D modelling of hydrodynamics and sediment dynamics of the DHI was selected to simulate and evaluate the movement of sediment on the Tien River through Cao Lanh district, Dong Thap province to propose technologies to predict erosion and sedimentation.

The study objectives are evaluation of hydraulic regime and sediment transport in the key landslide area at Cao Lanh - Dong Thap, thereby clarifying the hydrodynamic causes of landslides in the area. The research method to achieve the goal is: Successfully applying a 2-D hydrodynamic model to simulate the hydraulic regime and the sediment transport regime for the Tien river section, Cao Lanh district, Dong Thap province.

2. Materials and Methods

2.1. Theoretical module Mike 21FM HD

Module Mike 21 FM simulates the evolution of change and water level based on the equation of continuity and the equation of momentum in two directions [22]:

Equation of momentum:

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=hS \tag{1}$$

O_x direction:

$$\frac{\partial h\bar{u}}{\partial t}+\frac{\partial h\bar{u}^2}{\partial x}+\frac{\partial h\bar{v}\bar{u}}{\partial y}=f\bar{v}h-gh\frac{\partial \eta}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{bx}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y}\right)+\frac{\partial}{\partial x}(hT_{xx})+\frac{\partial}{\partial y}(hT_{xy})+hu_sS \tag{2}$$

O_y direction:

$$\frac{\partial h\bar{v}}{\partial t}+\frac{\partial h\bar{u}\bar{v}}{\partial x}+\frac{\partial h\bar{v}^2}{\partial y}=-f\bar{u}h-gh\frac{\partial \eta}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial y}- \tag{3}$$

$$\frac{gh^2}{2\rho_0}\frac{\partial\rho}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{yx}}{\partial x}+\frac{\partial s_{yy}}{\partial y}\right)+\frac{\partial}{\partial x}\left(hT_{xy}\right)+\frac{\partial}{\partial y}\left(hT_{yy}\right)+hv_sS$$

where t is the time (s); x, y are coordinates (m); η is the water level change (m); d is the heigh; h is the water depth (m); g is the gravity acceleration (m/s^2); f = 2Ω sinϕ - Coriolis (s^{-1}); ρ_0 is the density of water (kg/m^3); p_a is the atmospheric pressure (Pa/m); S is the discharge (m^3/s); u_s, v_s is the velocity (m/s); $\bar{u}$, v are the velocity average of flow depth (m/s); T_{ij} is the internal stress components, determined by the eddy viscosity formula based on the mean velocity with depth; τ_{sx}, τ_{sy} are the surface friction stress in the x and y phương directions (N/m^2); τ_{bx}, τ_{by} are the bottom friction stress in the x and y phương directions (N/m^2); A is the horizontal turbulence coefficient (m^2/s); S_{xx}, S_{xy}, S_{yx}, S_{yy} are components of wave radiation stress on unit volume of water in x and y directions (N/m^2).

The process of performing the simulation model as shown in Figure 1.

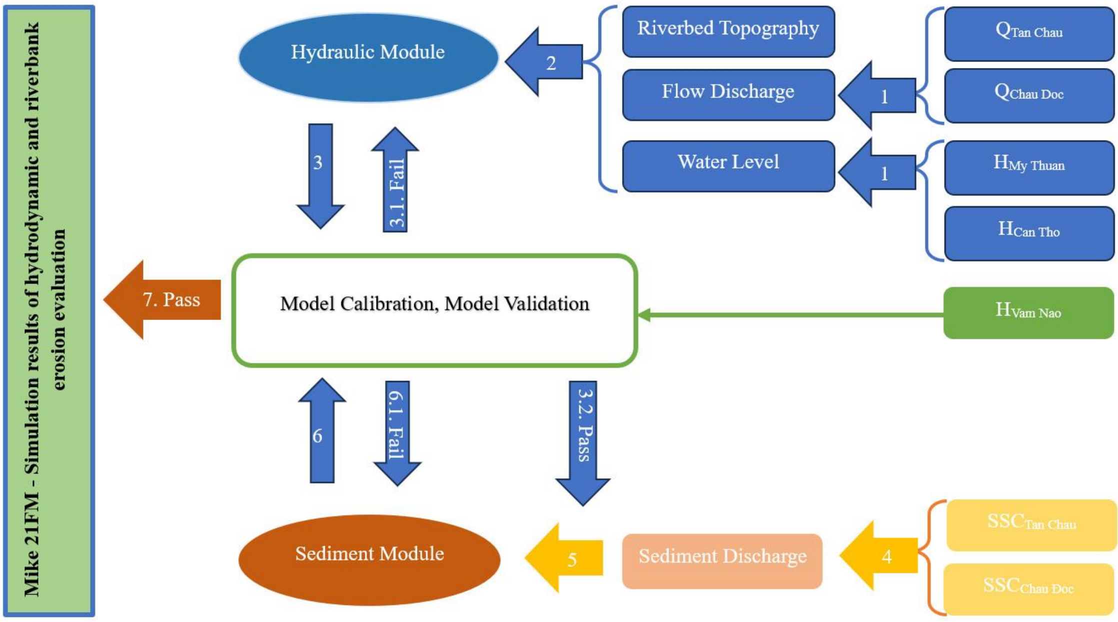

Figure 1. Flowchart of study structure [1–2].

2.2. Theoretical module MIKE 21FM-MT

The sediment transport module is set up based on the transport-diffusion equation [23]:

$$\frac{\partial\bar{c}}{\partial t}+u\frac{\partial\bar{c}}{\partial x}+v\frac{\partial\bar{c}}{\partial y}=\frac{1}{h}\frac{\partial}{\partial x}\left(hD_x\frac{\partial\bar{c}}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(hD_y\frac{\partial\bar{c}}{\partial y}\right)+Q_LC_L\frac{1}{h}-S \tag{4}$$

where t is time (s); x, y are coordinates (m); u, v are the depth-average velocity component in the direction x and y (m/s); h is the depth (m); $\bar{c}$ is the average concentration of suspended sediment by depth (kg/m^3); D_x, D_y are the diffusion coefficient in the x, y directions (m^2/s); S is the term of the source of sediment due to erosion or accretion ($kg/m^3/s$); Q_L is the discharge rate per unit cross-sectional area ($m^3/s/m^2$); $C_L$is the concentration of suspended sediment at the inlet (kg/m^3).

Simulate bottom morphology: The sediment volume of the i^{th} grain class in the j^{th} bottom layer of the elements in the grid is updated after each time step. The volume of the bottom layer is updated according to the following equation:

$$m_{i,j}^{new}=m_{i,j}^{old}+(D_i-E_i)\Delta t+\left(T_{i,j-1}-T_{i,j}\right) \tag{5}$$

where m is the volume of sediment (kg/m^2); D is the amount of sediment ($kg/m^2/s$); E is the amount of erosion ($kg/m^2/s$); T is the amount of moving sediment of the bottom layer ($kg/m^2/s$); Δt is time step.

2.3. Data

2.3.1. Computational domain

The computational mesh built for the computational domain is a flexible mesh network, including 8.126 nodes with 134.644 elements, fully representing the areas in the riverbed as well as the riverbank. The maximum length of the element is 45 m and the minimum length is 5 m describing the riverbed and riverbank area [1–2].

The topographic database used in the construction of the grid for hydraulic calculations for the study area is processed from topographic survey data performed by the project with a resolution of 20m × 20m. River topographic data of 3 typical study areas are measured by echosounder with integrated GPS positioning, the file is exported as ".txt", processed and cleaned into points by GIS tools (ArcGIS, Global Mapper, etc.) to include in the model for building elevation domain for the calculated area with detailed distance of 3-5m (Figures 2-3).

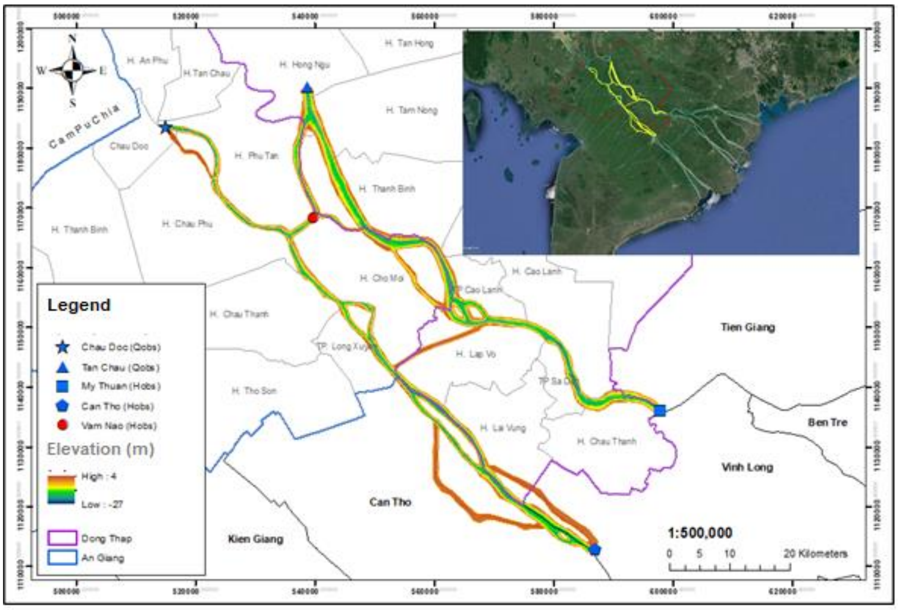

Figure 2. Domain study area.

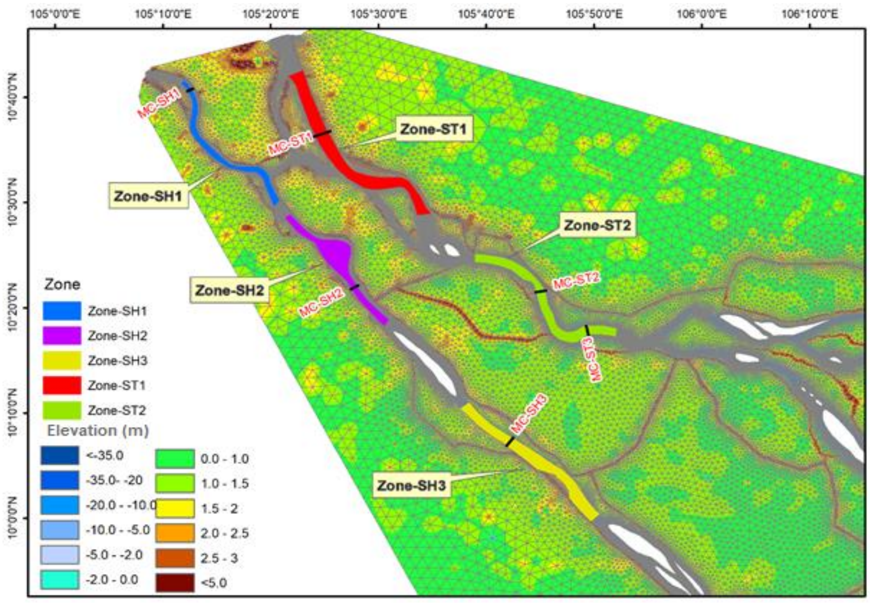

Figure 3. The location study area and calculation mesh.

2.3.2. Model setting

a) Boundary conditions

In this study, the team set up a 4-boundary domain, including 2 input boundaries to collect discharge and sediment data at Chau Doc hydrology station and Tan Chau hydrology station, 2 downstream boundaries to collect water level data at My Thuan hydrology station and Can Tho hydrology station. Select discharge and water level data at Vam Nao hydrology station to calibrate and verify the model [1–2].

Upstream boundary: Discharge margin taken at Tan Chau hydrological station and Chau Doc hydrology station, period data, from 00:00:00 01/01/2017–23/00/00 31/12/2019 (3 years). Sediment content margin (SSC) taken from Tan Chau station and Chau Doc station, day period data, from 01/01/2017–31/12/2019 (3 years).

Downstream boundary: Water level boundary taken at My Thuan hydrology station and Can Tho hydrology station, period data from 00:00:00 01/01/2017–23/00/00 31/12/2019 (3 years).

b) Modeling

The process, model testing is conducted after model calibration to check the reliability of the selected parameters with changed input factors:

- Hydraulic model calibration period: year 2000 and 2011.
- Hydraulic model verification period: 01/01/2018 to 31/12/2018.
- Sediment transportation model verification period: 01/01/2018 to 31/12/2018.
- Simulation and evaluation period: from 2017 to 2019.

The results of model correction will be shown in the hydrodynamic process including hydraulic factors such as: water level, velocity, and waves along with the sediment transport process such as the suspended sediment content in the flow. For the data of water level and suspended sediment will be adjusted in the dry season and verified in the flood season, while the flow velocity data due to lack of data should only be used for correction in the dry season.

3. Results and Discussion

In this study, flow measurement data, and sediment content (SSC) at Vam Nao hydrological station are used to calibrate and verify the model. These are two stations with good document quality, synchronous and long measurement data. The study uses solid measurement data in 2018 to calibrate and verify the model, calibrate in the dry season period (from January 2018 to June 2018) and verify during the flood season (from July 2018 to December 2018). For suspended sediment content, its evolution needs to be shown over a long time to be able to evaluate the reasonableness of the regularity, the study uses a continuous time series from January 2018 to December 2018 to calibrate and verify the model (Figures 4-5).

3.1. Calibration and validation of hydraulic model

Through the results of calculation of error indexes, the results of calibration and flow verification are good; NASH = 0.75-0.78 and the correlation coefficient is from 0.76-0.82. Therefore, it can be concluded that the model parameter set is stable and can be used for the setting and simulation step (Table 1).

Table 1. Calibration and verification results of the hydraulic model.

		R^2	NASH
Calibration	2000	0.74	0.73
	2011	0.80	0.72
Validation		**R^2**	**NASH**
	2018	0.78	0.76

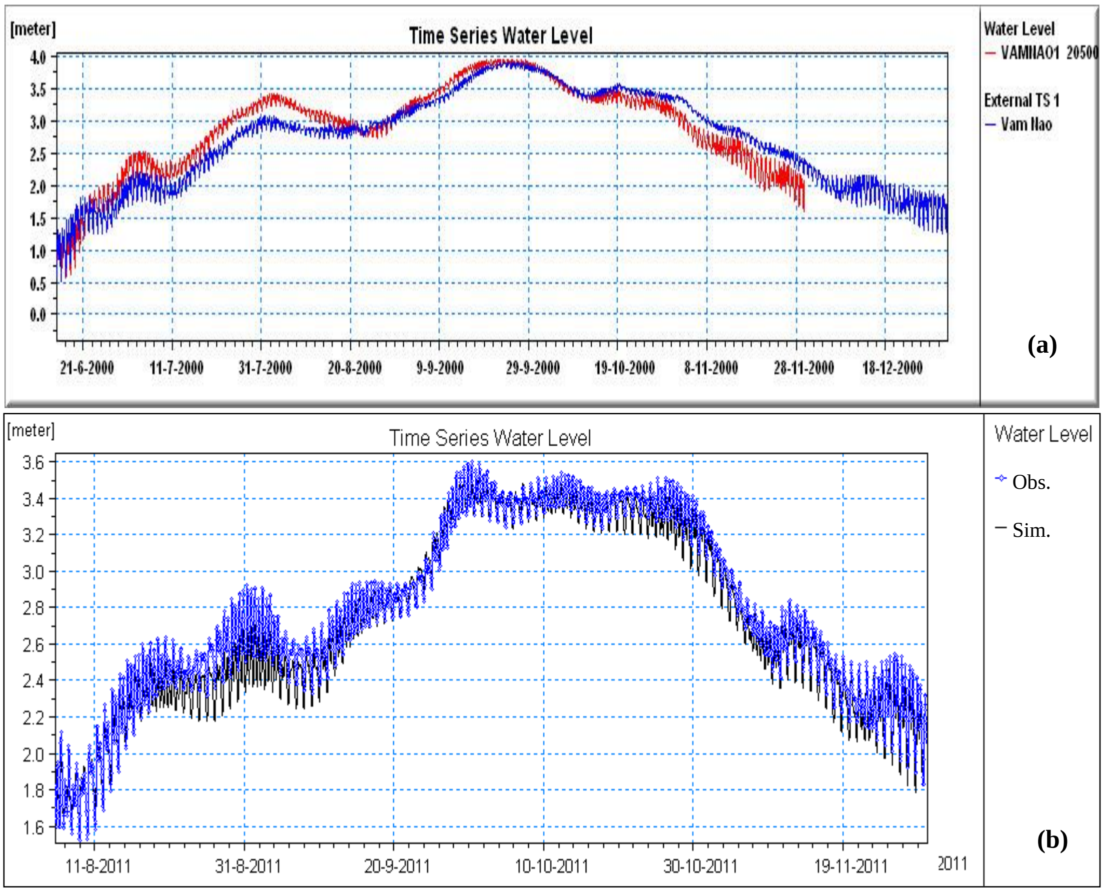

Figure 4. Results of calibration water level in Vam Nao station in 2000 and 2011.

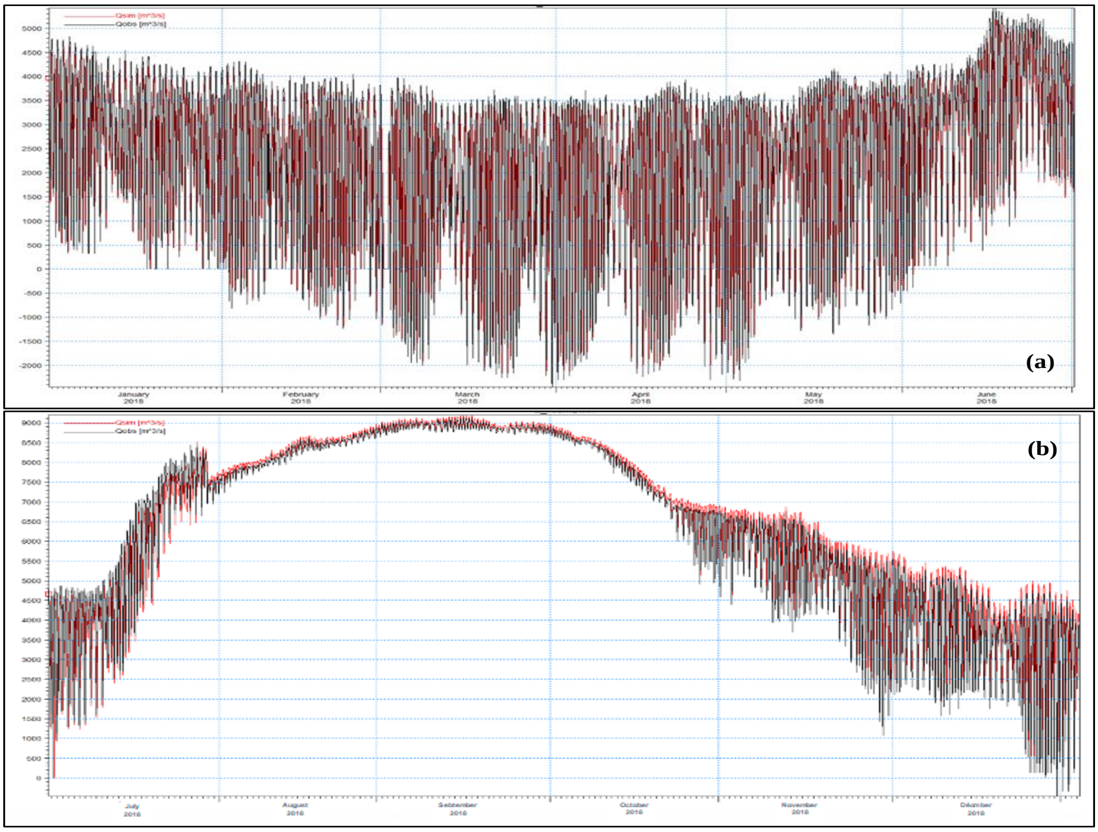

Figure 5. Results of verification discharge in Vam Nao station 2018.

3.2. Results of sediment transportation model calibration and verification

The results of calibration and verification show that the correlation index is relatively stable for the problem of sediment simulation - SSC and W_{bc} are 0.67 and 0.81 respectively, the Nash coefficient reaches a suitable value for the problem of sediment simulation - SSC's Nash is 0.67 and W_{bc}'s Nash is 0.77, especially the total error of the total amount reaches 6.54% - which is good (Figures 6-7 and Table 2).

From the total calculation data, it can also be seen that the seasonal change of sediment content is regular in accordance with the seasonal flow. Thus, the simulation results are good, showing that the model has high reliability.

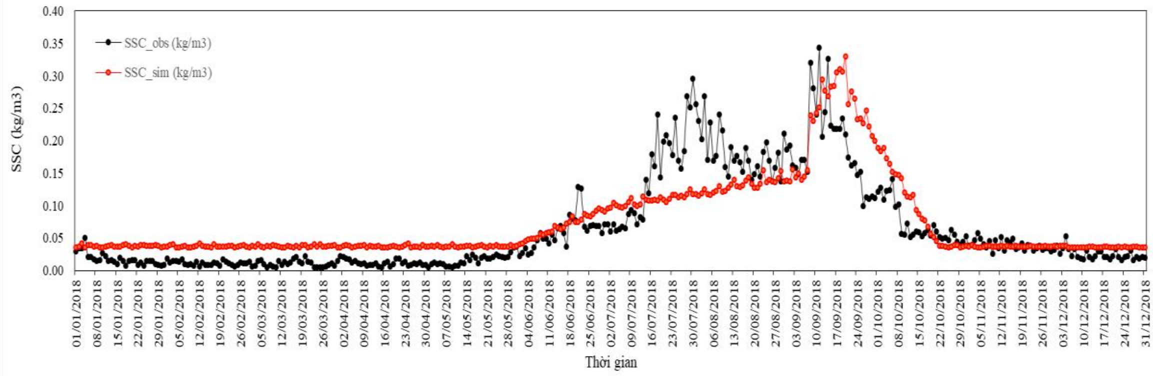

Figure 6. Results of calibration content of sediment (kg/m^3) in Vam Nao station.

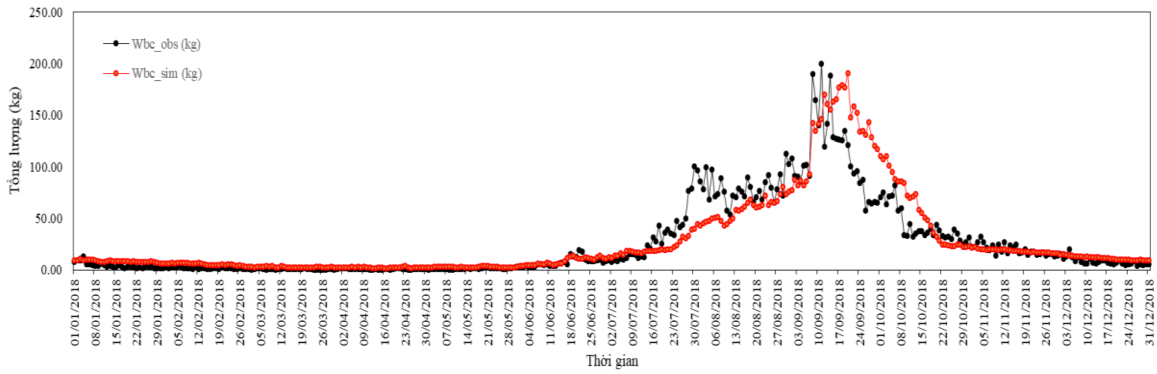

Figure 7. Results of calibration total amount of sediment (kg) in Vam Nao station.

Table 2. Results of calibration sediment in Vam Nao station.

Content of sediment in Vam Nao station	**01/2018 to 12/2018**		
	R^2	NASH	
	0.67	0.67	
Total amout of sediment in Vam Nao station	**01/2018 to 12/2018**		
	R^2	NASH	Total error
	0.81	0.77	6.54%

3.3. Simulation results of sedimentary changes

3.3.1. Water level and flow velocity

From the simulation results, it can be clearly seen that the difference between the largest and the lowest water level (H_{max}-H_{min}). This difference is also one of the causes of bank erosion in the area. In recent years, the landslide often occurs at the transition time between the flood head and the dry season, when the water level recedes too deeply, causing the banks to collapse (Figures 8-10).

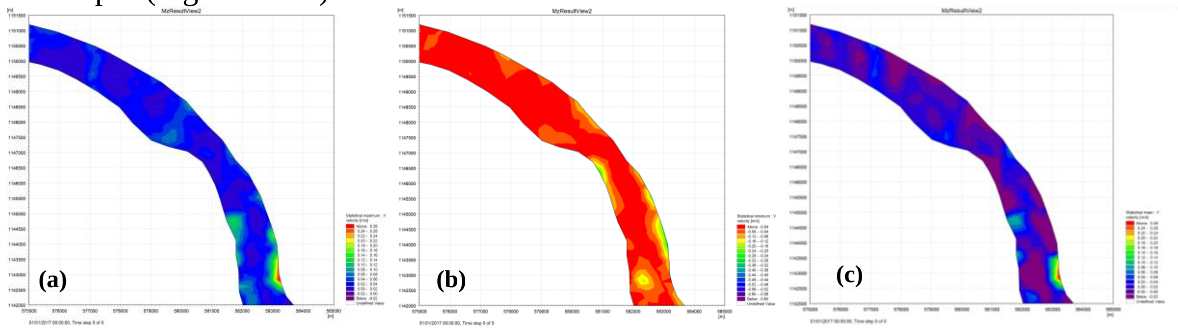

Figure 8. Calculation results of maximum (a), minimum (b), average (c) flow velocity in the study area.

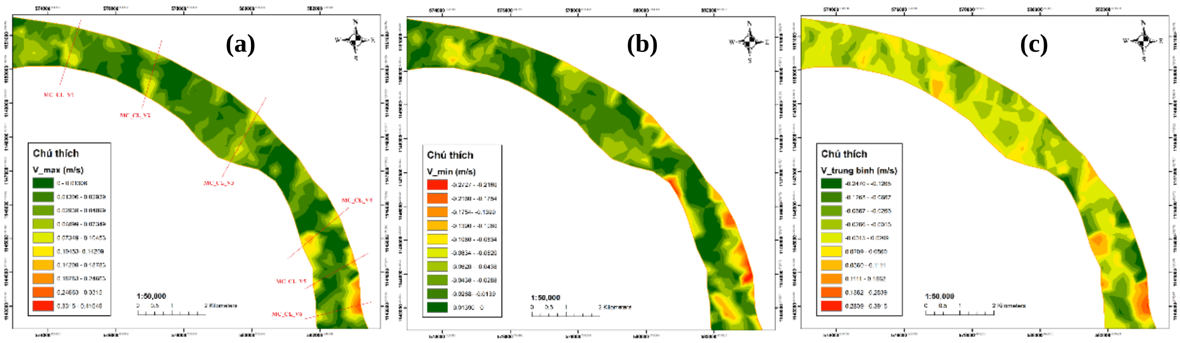

Figure 9. Map of maximum (a), minimum (b), average (c) flow velocity in the study area.

The variation of velocity is greatly influenced by the discharge regime from the headwaters and the ebb and flow of the tides. The location at Cao Lanh located on the Tien River has a higher input discharge, 80% compared to 20% of the Hau River, while the high tides at the estuaries remain unchanged, causing the tidal influence to increase, causing more or less influence on the flow rate, especially the amplitude V_{max} - V_{min} in the direction from upstream to downstream.

Due to that reversible interaction, the flow direction on the Tien and Hau rivers changes with the seasons. Hydrodynamic simulation results show that, in the dry season, the river flows in two directions (both negative and positive); During the flood season, the current flows in only one direction from upstream to the sea.

In general, the main flow from upstream to downstream of the river section in Cao Lanh area tends to be concentrated on both banks, with the maximum velocity region appearing close to the shoreline, extending 7.0 km from the CL_V3 section to the CL_V6 section.

3.3.2. Simulation result sediment

The results of calculating the largest amount of displaced sediment are based on the results of the simulation of the sediment model from January 2017 to December 2019. The largest amount of displaced sediment is concentrated mainly on the right bank where there is a complex hydraulic regime - creating deep erosion holes (Figure 10).

The section of the Tien River flowing through Cao Lanh is a curved section with many pre-existing erosion holes - and most of them are displaced holes - creating a severe left bank erosion area. The largest amount of mud displaced varies from 0.91 kg/m^3 to 32.7 kg/m^3.

At all sections, the largest amount of displaced sediment occurs on the right bank and ranges from 0.9 kg/m^3 to 2.7 kg/m^3. The left bank area is an area of curved river, so the amount of sediment removed is concentrated in this area. The research area at Cao Lanh is located under the sand mine, so the simulation process is quite affected by this problem.

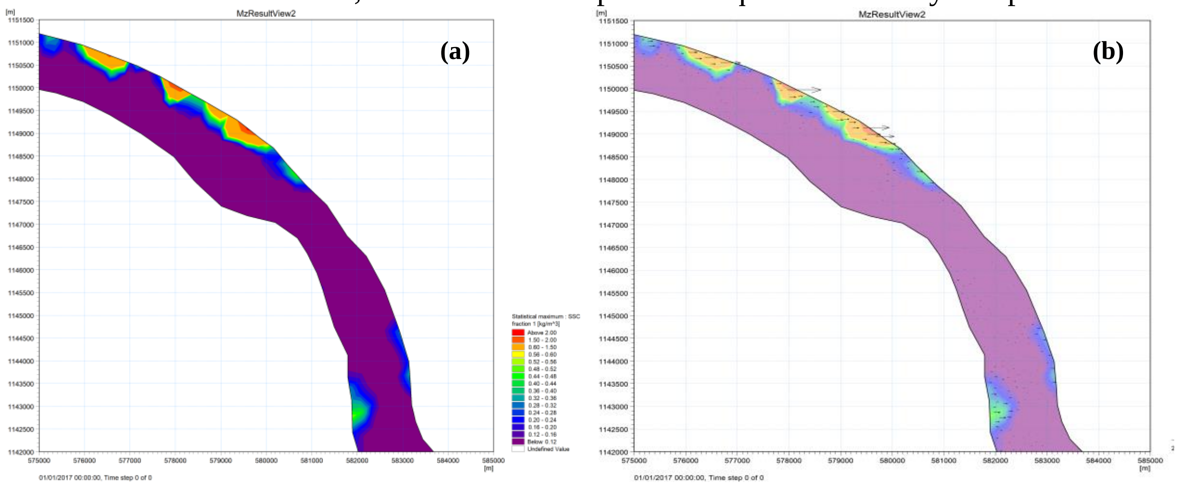

Figure 10. (a) Calculation results of the maximum concentration of sediment; (b) Direction of movement of the sediment.

3.4. Erosion trend in the study area

The simulation results show that, after 3 years, the total amount of sediment lost here and moved downstream is about -218.7,106 m^3, the depth of erosion after 3 years is -233 cm, the average erosion speed is -77.6 cm/year, where the deepest erosion can be up to -10.0 m (Figure 11).

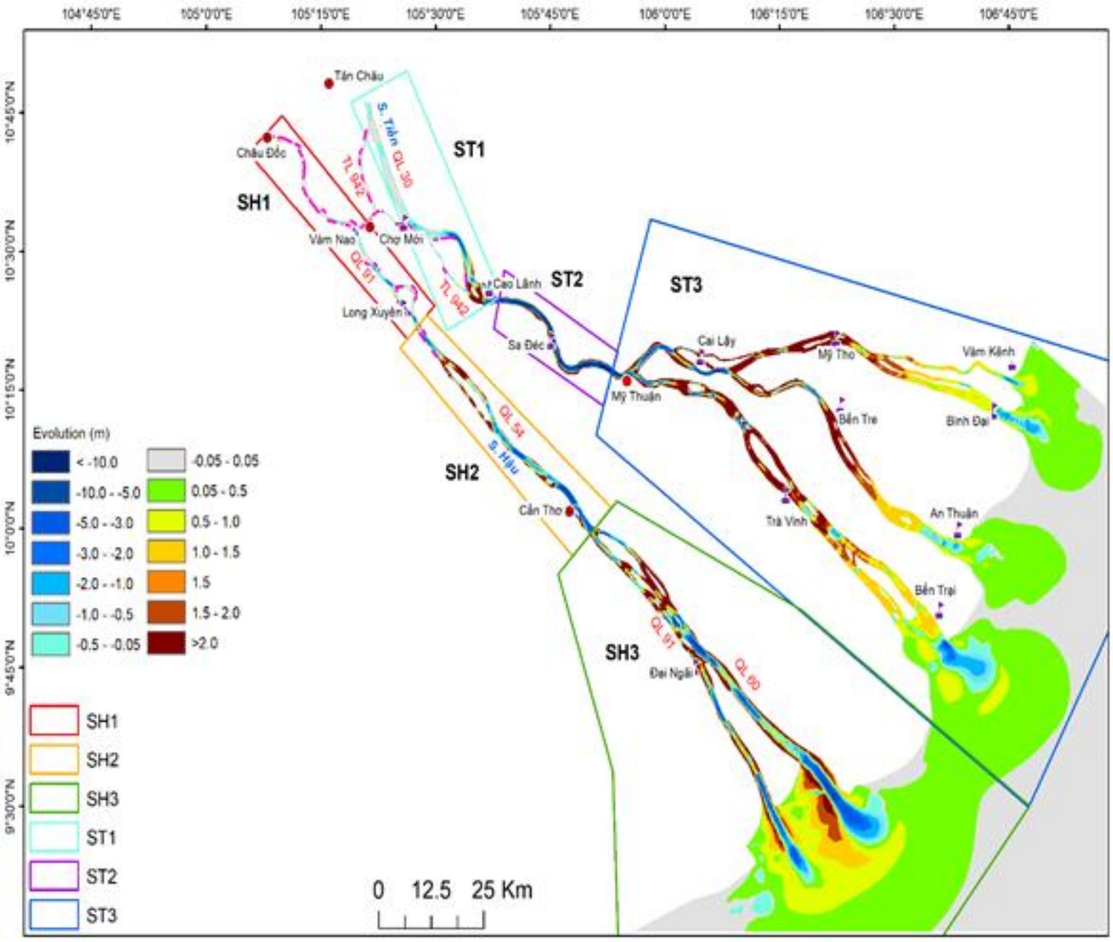

Figure 11. Morphological simulation results after 3 years (ST2 - area research).

Unlike the upstream area ST1, ST2 is considered as the middle area, so it can receive more sediments displaced from ST1, so the depth of erosion and loss of gradually decrease over time. However, this is an area with very high flow velocity, but it is curved, so the risk of landslides is great. This is an area where national highways QL30 and QL80 pass and in the future, it is necessary to have solutions to protect both sides of the river.

In general, the morphological characteristics of this area have a large degree of erosion and there is almost no large enough source of sediment to recover, the trend of deep erosion takes place and slows down over time. This is explained by the continuous deep erosion process, which increases the average wet section here, causing the flow velocity to decrease gradually, this area moves to a new equilibrium with decreasing phenomenon.

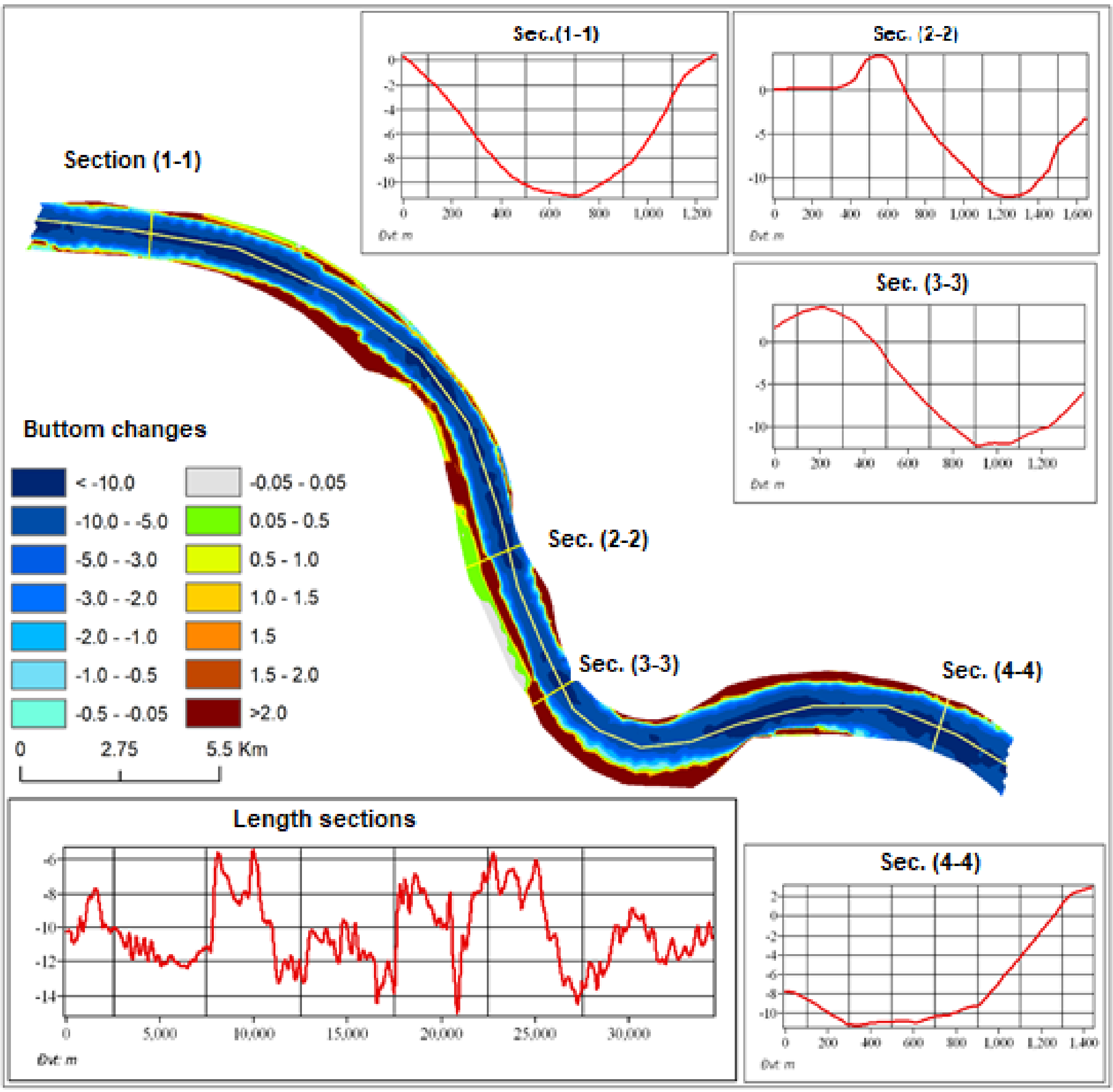

Figure 12. Morphological change of riverbed after 3 years.

The accumulation line of total sediment tends to go down, slow down over time and not be able to recover. The common feature of this area is that the accumulation line goes down sharply, due to the large flow rate, almost the amount of sediment moving from the upstream cannot settle here but is gradually carried out by the current towards the estuary. However, the simulation results show that, although the accumulation line goes down, it gradually decreases. Therefore, after many years, the ability to accumulate sediment here will gradually increase over time to re-establish a new balance (Figure 12).

4. Conclusion

By using mathematical modeling methods, specifically the Mike 21 FM model, the study calculated the sediment transport on the Tien River, passing through Cao Lanh district, Dong Thap province, thereby simulating the rate of erosion over a period of 3 years. The calculated results are highly reliable. The flow velocity in the river is unevenly distributed, at the bends that contribute to the increase in erosion, most evident at Sec. (2-2) and Sec. (3-3). The largest amount of sediment displaced ranged from 0.91 kg/m^3 to 32.7 kg/m^3. The total amount of sand moving is from the right bank and fluctuates from 0.9 kg/m^3 to 2.7 kg/m^3.

The trend of erosion in Cao Lanh district, Dong Thap province is shown as 12. The simulation results show that the total amount of sediment moving downstream is about -218,7106 m^3, equivalent to 72.9 m^3/year and the average erosion depth is -77.7 cm/year.

The results show that there is a certain suitability and sufficient reliability for the simulation of riverbed changes and can be used to calculate according to different input scenarios. The study area in Cao Lanh district tends to be dominated by erosion with accretion, which is consistent with the river topography. However, the limitation of the study does not consider the change of people's activities in the river and on the riverbank surface; does not consider the change of hydrogeological factors in the riverbank area; does not consider account the change of flow rate with hydrographic depth (3D); … will cause certain errors in the landslide hazard index results.

In fact, the new study is just a simulation based on the model parameters that have been calibrated and tested in Vam Nao. Therefore, it is necessary to have an assessment with reality in the study area over a longer period to show the reality of the model results. This result will be improved in the next research.

Authors contribution statement: Research ideas, build scientific: N.T.K., C.T.V., Research methodology: N.T.K., C.T.V.; Data collection and processing: N.H.T., H.T.T.N.; Write the manuscript and correct the article: C.T.V., N.H.T.; Editing and finishing: C.T.V.

Acknowledgments: This article uses data, the result is the product of a project at the University of Natural Resources and Environment of Ho Chi Minh City, code CT.2023.06. In addition, the study inherits data from the project of the Ministry of Natural Resources and Environment, code: TNMT.2018.02.13. The authors gratefully acknowledge this support.

Competing interest statement: The authors declare no conflict of interest.

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