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Influence of Grain Size on the Sediment Budget for Nourished Sand Bars in Hoi-An Area

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Abstract. The phenomenon of deposition and erosion on Hoi An beach in recent years has been the research topic of many organizations and researchers. Many solutions have been proposed to mitigate the erosion and one of the selected solutions for coastal protection is the nourished sand bars. This approach has the benefit of preserving the natural scenery of the tourist beach, as a certain amount of sand needs to be added each year to maintain shore protection against the waves and winds prevalent in the area. The size of the sand grains plays a critical role in the efficacy of the sand trap. This research employs the Telemac numerical model, which integrates problem-solving with hydrodynamics and coastal wave calculations, to quantitatively analyze the impact of sand grain size on the time-average expected sand deposition under various scenarios. The simulation results indicate an inverse correlation between the average diameter of sand grain size and the required amount of additional sand, as well as the effect of extreme weather conditions such as increased waves and wind on the amount of sand needed for nourished sand bars.

Keywords: Coastal deposition · Coastal erosion · Grain size · Hydrological characteristic · Nourished sand bars

1 Introduction

Observations in recent years indicate an increasing rate of erosion and sedimentation at the Cua-Dai river and along the Hoi An coastline. Several studies by various organizations and individuals have already addressed this issue [1, 5]. Considering the vital role of tourist-serving beaches in coastal protection, a proposed experimental solution is beach nourishment, requiring the yearly addition of a certain amount of sand to offset annual sand loss. To manage the extraction process proactively, it is crucial to estimate the volume and type of sand to be replenished. This study aims to explore different scenarios

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J. N. Reddy et al. (Eds.): ICSCEA 2023, LNCE 442, pp. 1890–1898, 2024.
https://doi.org/10.1007/978-981-99-7434-4_204

with varying average grain sizes of sand and corresponding quantities to be replenished after each flood season. Considering the most likely erosion occurrences throughout the year, the simulation will be conducted from October 2018 to March 2019, corresponding to the peak activity of the Northeast monsoon winds in the region. To examine sediment transport processes, a numerical modeling approach will be utilized, integrating the theoretical principles of hydrodynamic problems using the Telemac2D module, wave problems using the Tomawac module, and morphodynamic problems of channel deformation using the Sisyphe module. All these modules have been developed by Electricité de France (EDF) in collaboration with European and American laboratories and are widely used open-source models worldwide.

2 Numerical Model

Telemac2D is one of the hydraulic software programs led by Electricité de France (EDF), in collaboration with various research organizations worldwide, used for simulating two-dimensional flow in the horizontal plane (averaged in the vertical direction) described by the Saint-Venant equations including Eqs. (1), (2), and (3).

$$\frac{\partial y}{\partial t} + div(h\overrightarrow{U}) = q \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial Z_s}{\partial x} + F_x + \frac{1}{h}div\left[h\nu_e grad(u)\right] \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial Z_s}{\partial y} + F_y + \frac{1}{h}div\left[h\nu_e grad(v)\right] \tag{3}$$

where, h (m): water depth; u & v (m/s): horizontal components of velocity in the x and y directions, respectively; q (m/s): water discharge; Zs (m): free surface elevation; F_x, F_y (m/s^2): external forces (excluding gravity, such as Coriolis force) act on a unit mass projected horizontally in the x and y directions respectively; ν_e (m^2/s)-diffusion coefficient.

The Telemac2D model is programmed to be able to choose between finite element or finite volume methods. The numerical problem can handle various types of boundary conditions, such as water level (Z), discharge (Q), discharge and water level (Q&Z), velocity (u, v), velocity and water level (u, v & Z), or wave boundary conditions.

Under the influence of wind on the ocean surface, wave phenomena occur. The physical phenomenon is described by an equation representing the variation of wave spectral density in the direction, as given by Eq. (4), and solved by the numerical wave model Tomawac developed by the French Power Company.

$$\frac{\partial N}{\partial t} + \frac{\partial \ddot{x}N}{\partial x} + \frac{\partial \ddot{y}N}{\partial y} + \frac{\partial \dot{k}_x N}{\partial x} + \frac{\partial \dot{k}_y N}{\partial y} = Q(k_x, k_y, x, y, t) \tag{4}$$

where, $N\left(\overrightarrow{x}, \overrightarrow{y}, \overrightarrow{k}, t\right) = N\left(x, y, k_x, k_y, t\right)$: spectrum of wave energy density; $\overrightarrow{x} = (x, y)$: the position vector in Cartesian coordinate system; $\overrightarrow{k} = \left(k_x, k_y\right) = (k\sin\theta, k\cos\theta)$: wave vector; θ is the wave direction

The deformation phenomenon of the sediment bed in the research domain is associated with two forms of sediment transport: bedload transport and suspended load transport. The two-dimensional suspended sediment transport in the horizontal direction is described by Eqs. (5) and (6).

$$\frac{\partial hC}{\partial t} + \frac{\partial (hUC)}{\partial x} + \frac{\partial (hVC)}{\partial y} = \frac{\partial}{\partial x}\left(h\varepsilon_s \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\varepsilon_s \frac{\partial C}{\partial y}\right) + E - D \tag{5}$$

$$(E - D)_{Zref} = \omega_s \left(C_{eq} - C_{ref}\right) \tag{6}$$

where, C = C(x, y, t): the vertical average concentration of suspended sediment; $h = Z_s - Z_f \approx Z_s - Z_{ref}$: the water depth, assuming a thin layer of bed sediment; (U, V): the average velocities in the x and y directions, respectively; E: the erosion rate; D: the deposition rate; (E − D): the net sedimentation rate of suspended sediments; C_{eq}: the concentration of suspended sediment in the near-bed equilibrium state; C_{ref}: the concentration of suspended sediment at the bed level.

3 2D Hydrodynamic and Sediment Transport Modeling of the Estuary and Coastal Area of Hoi an

3.1 Calculation Domain

The modeled domain includes the lower Thu Bon River network in the Hoi An-Cua Dai area, along with a portion of the Hoi An coastal area as shown in Fig. 1. The coastline extends for approximately 30 km, with an average width of about 30 km from the shore. The calculation domain covers an area of approximately 817 km^2, which includes 20 km of the Vu Gia-Thu Bon river system in the downstream region and the coastal area near the river mouth. This coastal area extends 10 km to the north and south and approximately 27 km to the north. The domain is discretized into 43,381 triangular elements using a structured mesh, with the largest element edge size being 2000 m and the smallest element edge size in the Thu Bon River area being 50 m. The computation area for the unstructured mesh nourishment covers an average edge size of 15 m.

3.2 Boundaries Conditions

The modeled domain includes two discharge boundaries on the two main river branches in the upstream region, located approximately 12 km upstream from Cua Dai in a straight line. Due to the lack of available data for the same period, preliminary references can be made to the Nong Son and Thanh My hydrological stations, which are 25km and 60km, respectively, compared to the downstream estuary. The larger river branch (after Cau Lau Bridge) and the smaller branch (southern branch, located 12 km upstream from Cua Dai Bridge) are considered as shown in Fig. 2**.** The wave data from the offshore region for the same period was obtained from the NOAA database as shown in Fig. 3.

The influence of wind (spatial and temporal variations) on the flow is also taken into account. The following figure shows a typical Northeast Monsoon wind rose diagram for November 2014 at the Cua Dai location. The maximum wind speed reaches up to

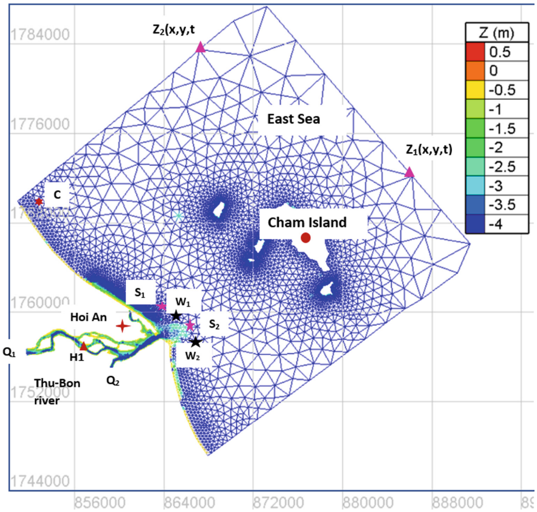


Fig. 1. Calculation mesh

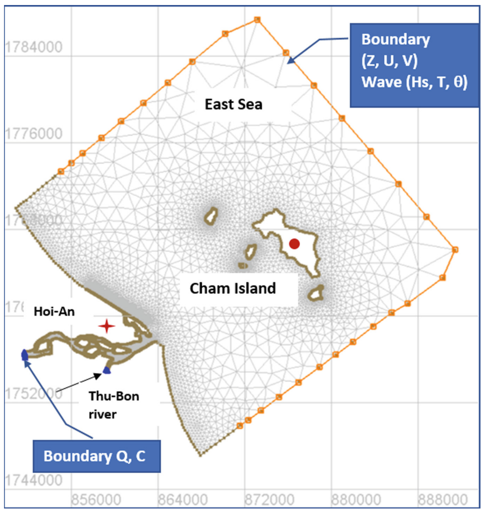


Fig. 2 Boundary conditions

12.7 m/s during the period when the area is affected by the Northeast Monsoon winds as shown in Fig. 4.

The calculation of sediment transport in this study assumes that the sediment is non-cohesive. The distribution of bed sediment is assumed to be uniform throughout the entire study area. The typical distribution of riverbed sand consists of representative particle sizes of 0.1 mm, 0.5 mm, 0.8 mm, and 1.5 mm, with respective proportions of 4%, 65%, 26%, and 5%.

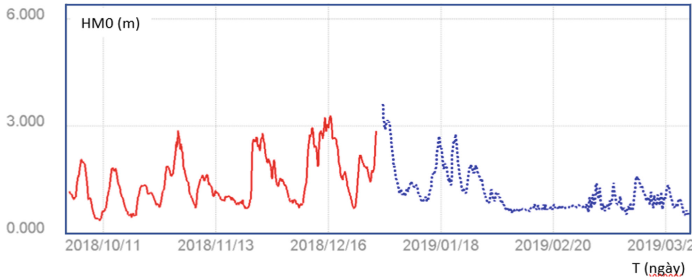


Fig. 3. Wave height (Hm0) at the representative point Z1 on the boundary during the simulation period from October 1, 2018, to March 31, 2019

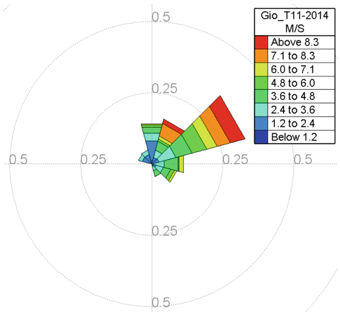


Fig. 4. Wind data in November 2014

3.3 Model Calibration and Validation

3.4 Hydraulic Model Calibration

The hydrodynamic model is calibrated and validated using the observed data at location H1, wave calibration is done at locations S1 and S2, and sediment calibration is performed at location C (Fig. 1). The model is calibrated using the data from October 2014 as follows. The graphs and the results of the harmonic analysis are presented in Fig. 5. The results from Fig. 5 indicate that the four main tidal constituents, K1, O1, M2, and S2, show relatively consistent and compatible results between the simulation and observed data.

3.5 Wave Model Calibration and Validation

The model is also calibrated using the wave data observed from October 16, 2014, to November 12, 2014, as shown in Fig. 6.

The results from the mentioned graphs generally show that the time series of the observed data is relatively smoother compared to the calculated results. This is reasonable in practice, as the time step for the observed data (1 h) is much larger than the computational time step of the model (10 s). The waves in October 2014 appear to be larger compared to those in April 2014. This is consistent with the natural trend of the

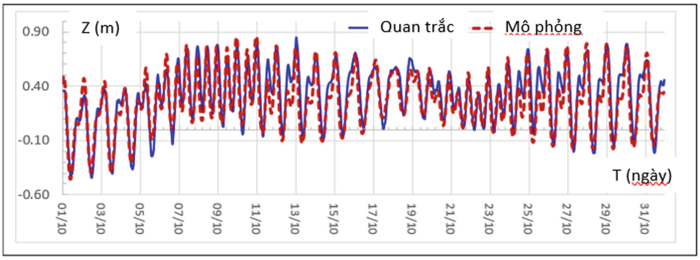
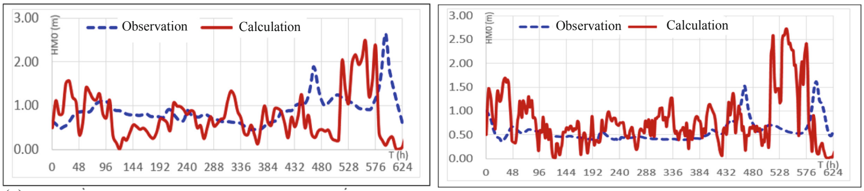


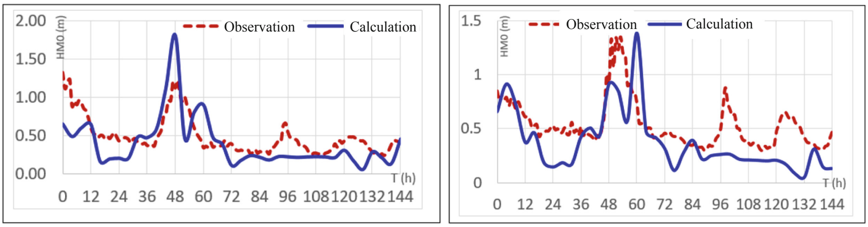
Fig. 5. Water level comparison between the simulation and observed data during the flood season in October 2014 at location H1



(a) (b)

Fig. 6. Wave height (HM0) at location **a** S1 and **b** S2 from October 16 to November 12, 2014

area. The wave model calibration results as shown in Fig. 7 indicate that the model calibration is relatively good.



(a) (b)

Fig. 7. Wave height (HM0) at location **a** W1 and **b** W2 from October 19, 2016 to October 25, 2016

3.6 Sediment Transport Model Calibration

Figure 8 shows sediment data at location C from June 4, 2016, to June 9, 2016. Comparison of the results obtained from the small-scale sediment simulation with the observed values reveals potential factors contributing to the discrepancies. These factors may include geological data used in the model which may not accurately represent the real-world conditions, leading to deviations in the simulated sediment behaviour. The numerical model employed for simulating sediment transport may be a mixed model that is not entirely suitable for the specific scenario, resulting in inconsistencies in the results. Sediment data measurements could have errors due to the complex sampling conditions in coastal areas, where multiple risks can impact the sampling technique. Overall, the small-scale sediment simulation results have the potential to diminish the accuracy of sediment deposition and erosion values derived from the simulation.

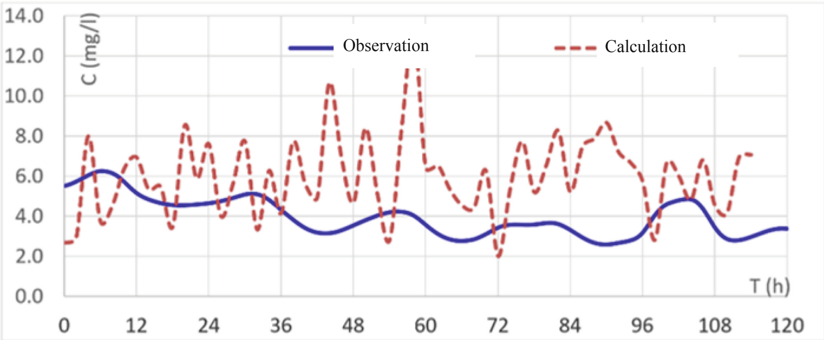


Fig. 8. Sediment data at location C from June 4, 2016, to June 9, 2016

4 Result and Discussion

In order to evaluate the influence of sediment grain size on the nourishment volume for the beach, calculations were conducted for a coastal area with a length of 3 km and a width of 300 m extending from the coastline at Hoi An beach. Four typical sediment grain size scenarios were considered: 0.4 mm, 0.6 mm, 0.8 mm, and 1.0 mm. Based on the observed wave and wind data obtained from global datasets, which are assumed to represent the most severe erosional conditions occurring during the Northeast monsoon season, the simulation period was selected from October 2018 to March 2019. Figures 9 and 10 show that the influence of wave breaking on the concentration of suspended sediment along the coastal area. The bed elevation of the Thu Bon River and the coastal zone of Hoi An shows a tendency towards erosion during the simulated period, as depicted in Fig. 10.

Table 1 shows summary of sediment transport variation based on 0.4 mm sediment diameter.

Based on the results in Table 1, the following observations can be drawn:

- The amount of sediment required for beach nourishment annually is inversely proportional to the sediment diameter. This result suggests a reasonable trend as smaller sediments are more easily carried away by the flow compared to larger sediments. For the considered area of 3 km × 300 m = 300,000 m^2, the average sediment diameter of 0.4 mm would result in an eroded layer thickness of 15.3 cm, while the case of an average sediment diameter of 1.0 mm would result in a thickness of 4.8 cm.

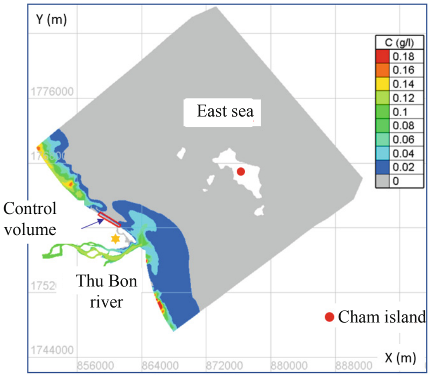


Fig. 9. Suspended sediment at on 09/12/2018

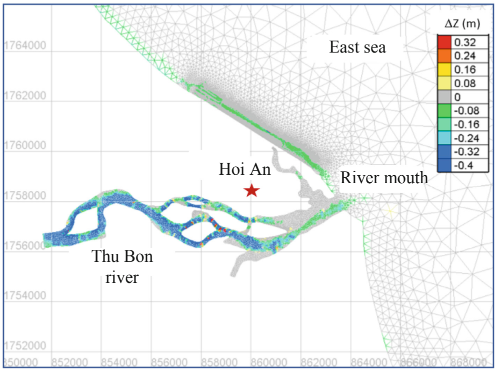


Fig. 10. Bed elevation changes from 10/2018 to 11/2018

Table 1. Summary of sediment transport variation based on typical sediment diameter

	From 10-2018 to 12-2018	From 1-2019 to 3-2019	Note
Typical diameter D_m (mm)	m^3	m^3	Negative value presents sediment transported out of control volume
0.4	−26138	−19796	
0.6	−17444	−12179	
0.8	−13625	−11973	
1.0	−7756	−6863	

- The sediment transport rate tends to decrease towards the end of the Northeast monsoon season. This observation may have a strong connection to the intensity of wave action during the simulated period, as illustrated in Fig. 3.

- The rate of sediment nourishment decreases rapidly as the sediment diameter for nourishment increases. This relationship follows a non-linear pattern.

5 Conclusion

Based on the aforementioned findings, we can draw several key conclusions regarding the impact of sediment diameter on sediment nourishment during the Northeast monsoon season at the typical location of Hoi An beach. Firstly, increasing the average sediment diameter in the nourishment area significantly reduces the required amount of sediment for annual nourishment. This observation can be attributed to larger sediments being less susceptible to being carried away by the average coastal flow compared to smaller sediments. Secondly, waves play a crucial role in the erosion process and contribute to the annual sediment loss. The rate of sediment nourishment increases more rapidly with rising wave intensity. This phenomenon can be explained by the higher concentration of suspended sediments when larger waves approach the coast, combined with the average coastal flow, which transports more sediment away from the nourishment area. And lastly, the presented results should be taken as reference data since the simulation was conducted for the period from October 2018 to March 2019. To establish quantitative relationships for sediment nourishment, longer simulations and consideration of multiple scenarios are necessary. This approach will enhance the reliability of statistical data and enable the development of valuable empirical formulas for operational management. The study's findings will enable potential project investors to identify a suitable sand source for the nourishment of sandbars.

Acknowledgments. We acknowledge Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for supporting this study.

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