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Shoreline evolution in adjacent to a coastal structure in Hiep Thanh commune, Duyen Hai district, Tra Vinh province

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ABSTRACT

Coastal erosion is significant along the coastline in Hiep Thanh commune, Duyen Hai district, Tra Vinh province, Viet Nam. In order to address this severe coastal erosion, the local community has constructed a concrete embankment as an emergency solution to protect the coastline. However, this solution exacerbates the issue since the fundamental processes of coastal erosion remain inadequately explored and understood. Specifically, in beach sections without the concrete embankment, erosion still occurs. Therefore, this paper aims to investigate the shoreline changes adjacent to the embankment using an integrated approach with remote sensing and diffusion theory. The results show that beach erosion is occurring near the embankment at a rate of 44 meters per year, and the diffusion coefficient for longshore sand transport in the study area is 130 square meters per day. This study offers a practical approach to examining changes in the shoreline adjacent to a coastal structure, particularly valuable in situations where there is a scarcity of measured field data.

1. INTRODUCTION

Along the coastline of the Mekong Delta in Viet Nam, there has been a significant coastal erosion in recent years (Anthony et al., 2015) due to many reasons such as sand starvation (Jordan et al., 2019) in the rivers or mangrove forest destruction (Besset et al., 2019).

Tra Vinh is a coastal province located in the east of the Mekong Delta (Figure 1) and coastal erosion is significant along the coastline in Hiep Thanh commune, Duyen Hai district, Tra Vinh province (Lan et al., 2019).

To address severe coastal erosion, the local community has erected a concrete embankment as an emergency measure to safeguard the coastline (highlighted by the yellow rectangle in Figure 1). Nevertheless, erosion persists in beach sections lacking this protective barrier (indicated by the red circle). Given the inadequate study of beach erosion mechanisms in this area, this paper aims to investigate shoreline erosion adjacent to the concrete embankment using an integrated approach incorporating remote sensing and diffusion theory.

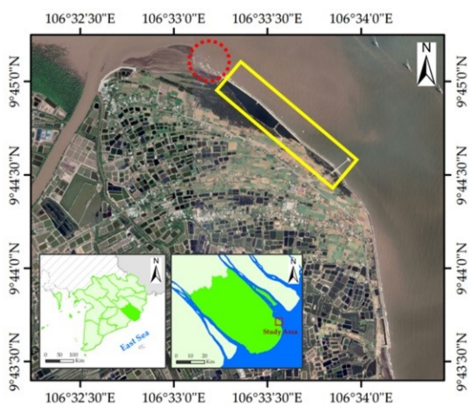


Figure 1. The study area

The results show that beach erosion is happening near the embankment at the rate of 44 m/year and the diffusion coefficient for longshore sand transport at the study area is 130 m^2/day.

Figure 2 shows the concrete embankment and the coastal erosion of the beach adjacent to the embankment.

Figure 2. The embankment and coastal erosion as depicted as yellow rectangle and red circle in Figure 1

2. MATERIALS AND METHOD

The research diagram is shown in Figure 3. As can be seen in Figure 3, Sentinel-2 images will be collected to observe the evolution of the shoreline from 2021 to 2023. After that, measured data such as wave conditions at the study area are collected to support the modelling of shoreline evolution using the theory of one-line model.

The measured shoreline change and the modeled shoreline change will be compared to find the optimal value of the longshore sediment transport (ε). The root mean squared error (RMSE) between the measured shoreline, and the modelled shoreline is calculated to find the optimal value of ε corresponding to the minimum RMSE.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(y_i - y_i\right)^2}{n}} \quad (1)$$

where y_i is the modelled shoreline position and y_i is the measured shoreline position at instant i, respectively.

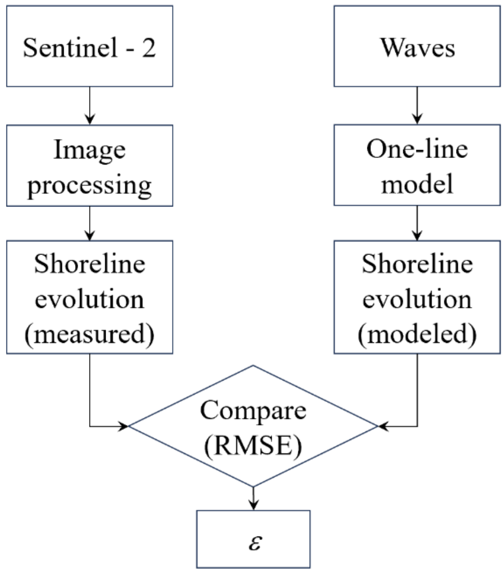


Figure 3. The research process

2.1. Satellite image analysis

Sentinel-2 images from 2021 to 2023 are used to observe the shoreline change in the study area. The information on the Sentinel-2 images used in this study is shown in Table 1.

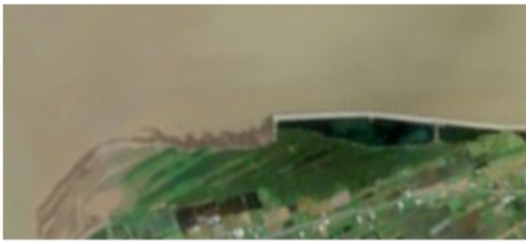
Table 1. Information of Sentinel-2 images

No.	Date	Sensor	RES (m)	Source
1	3 March 2021	MSI	10	Sentinel-2
2	7 April 2021	MSI	10	Sentinel-2
3	2 May 2021	MSI	10	Sentinel-2
4	1 February 2022	MSI	10	Sentinel-2
5	27 April 2022	MSI	10	Sentinel-2
6	13 March 2023	MSI	10	Sentinel-2
7	2 May 2023	MSI	10	Sentinel-2
8	6 July 2023	MSI	10	Sentinel-2

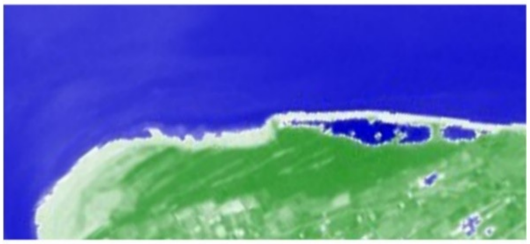
All the images after being collected will be processed to extract the shoreline using the NDWI index as follows (Xu, 2006):

$$NDWI = \frac{X_{green} - X_{nir}}{X_{green} + X_{nir}} \qquad (2)$$

where *Xgreen* and *Xnir* are the GREEN and NIR wavelengths, respectively. An example of calculating the NDWI for the Sentinel-2 images at the study area is shown in Figure 4.



True color



NDWI

Figure 4. Example of NDWI image at the study area

In this study, a Cartesian coordinate system was used consistently for the analysis. In which, the abscissa is 37.65^0 counter-clockwise from the north and crosses the point O (669,820.63 mE; 1,078,385.39 mN) in the UTM system (Figure 3).

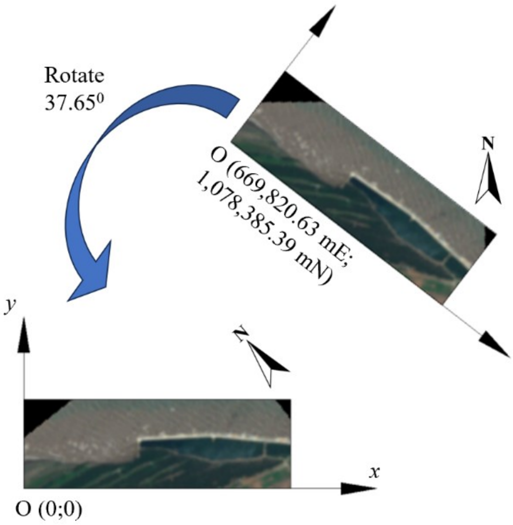


Figure 5. The coordinate system used in this study

2.2. Analytical modeling

The simple idea of one-line model (Figure 6) was used for the modeling of shoreline change at the study area. In the one-line model (Pelnard-Considère, 1957), it was assumed that the beach profile maintains an equilibrium, indicating that all submerged contours run parallel. Consequently, this assumption allows for the utilization of a single line to represent the shoreline's position as depicted in Figure 6.

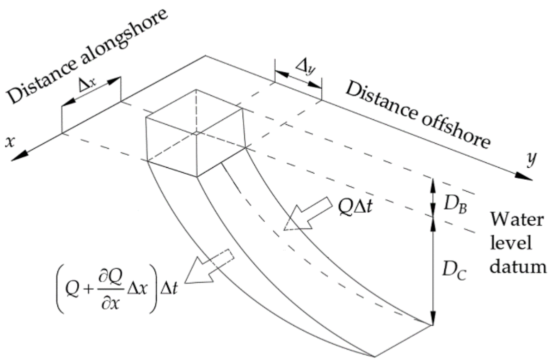


Figure 6. Diagrammatic representation of a theoretical balanced shoreline configuration

By examining a sand control volume and developing a mass balance over an infinitesimal time interval, the following differential equation is derived:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad (3)$$

where:
Q = longshore sand transport rate (m^3/s)
A = cross-sectional area of the beach (m^2)
x = alongshore coordinates (m)
t = time (sec)

Equation (3) asserts that alterations in the sand transport rate along the shore are offset by shifts in the shoreline position.

Larson et al. (1987), based on the idea of the one-line model, presented an analytical solution describing the interruption of sand transport alongshore caused by coastal structures such as groins or embankment to quickly investigate the basic physics involved to a satisfactory level of accuracy of beach behavior as follows (Larson et al., 1987):

$$y(x,t) = 2\tan\alpha_0 \left[\sqrt{\frac{\varepsilon t}{\pi}} \exp\left(-\frac{x^2}{4\varepsilon t} \right) - erfc\left(\frac{x}{2\sqrt{\varepsilon t}} \right) \right] \qquad (4)$$

where:

α_0 is the orientation of breaking wave crests in relation to the x-axis

ε is the diffusion coefficient representing the ability of wave energy to transport sand along the shoreline

t is the time

erfc = complementary error function

To simulate the shoreline evolution at the embankment using Equation (4), we conducted a thorough compilation of the necessary initial variables, with their corresponding values provided in Table 2. The rationale for selecting specific values for each variable is elaborated in the subsequent paragraphs.

Table 2. Initial values of variables used for modeling the shoreline evolution at the embankment

Parameters	Values
Diffusion coefficient, ε (m^2/day)	Unknown
Simulation time, t (years)	2.34
x (m)	600
Breaking wave angle, α_0 (degrees)	15

The unknown diffusion coefficient for longshore sand transport (ε) is the subject of calculation in this study.

The simulation time followed the measured shoreline positions extracted from image analysis over the period spanning from 3 March 2021 to 6 July 2023 (equivalent to 2.34 years).

The shoreline evolution is extracted at the cross-section of x = 600 m along the shore (see Figure 9).

In order to determine the breaking wave angle α_0, measured wave data from 02/09/2020 to 05/09/2020 at the study area are used. The location of wave gauge and wave rose are shown in Figure 7 and Figure 8. The COASTEXCEL tool (Sana, 2017) was used to transform wave from the deep water to the breaking zone. The result of wave transformation yields $\alpha_0 = 15^0$. This breaking wave angle is kept constant to model the shoreline evolution using the analytical solution as presented in Equation (4).

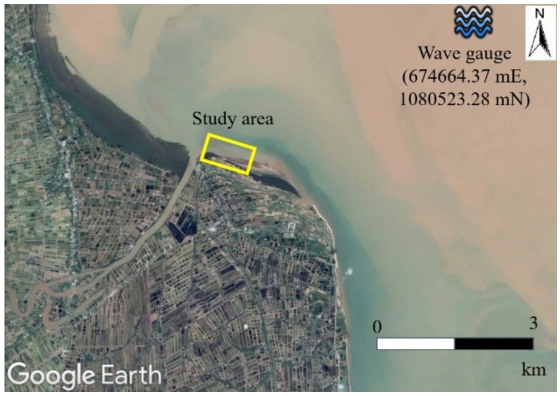


Figure 7. Location of wave gauge

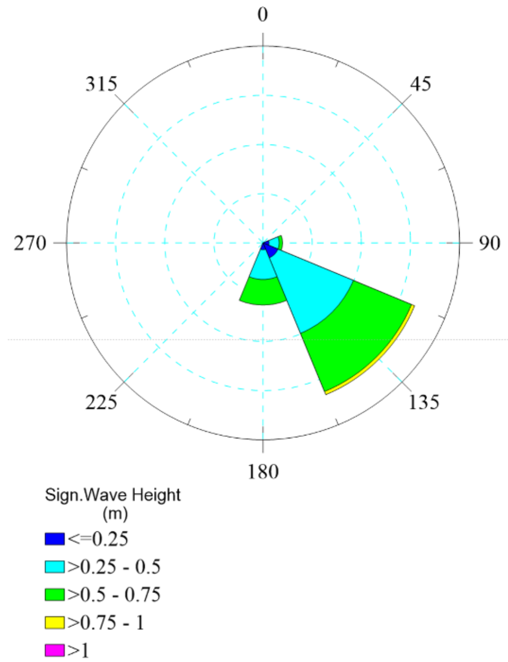


Figure 8. Wave rose

3. RESULTS AND DISCUSSION

3.1. Shoreline change

The shoreline positions at various intervals from 03 March 2021 to 06 July 2023 are depicted in Figure 9. As evident from the figure, significant coastal erosion has occurred near the embankment. Specifically, at the cross-section of x = 600 m, the shoreline has retreated approximately 100 m over the past two years.

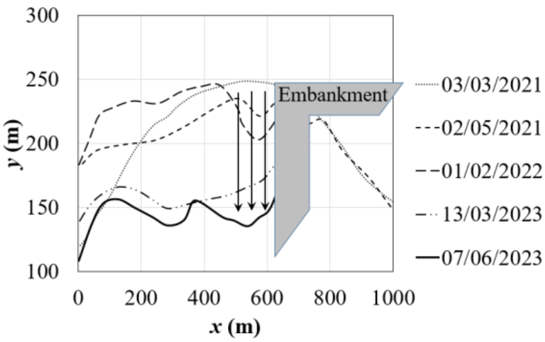


Figure 9. Shoreline changes near the embankment

To quantitatively assess the shoreline change rate, we plot the shoreline evolution of the section x = 600 m in Figure 10. In which, the red dots represent the temporal variation of the shoreline positions and the blue solid line represents the trend line (linear regression) of the shoreline evolution. The R^2 = 0.919 indicates that the linear regression method well predicts the trend of the shoreline evolution (Dolan et al., 1991).

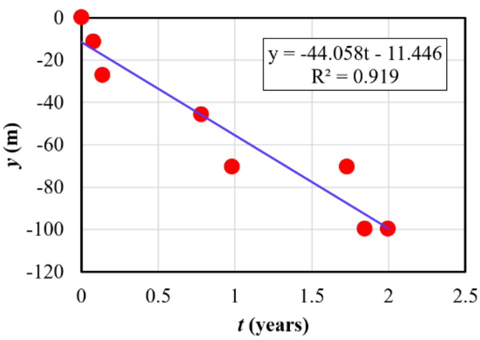


Figure 10. Shoreline evolution at *x* = 600 m

From Figure 10, the equation of the linear regression line yields:

$$y = -44.058t - 11.446 \quad (5)$$

Since Equation (5) has the form of a simple linear regression, the scaling factor β can be determined as –44.058 m/year. In other words, the shoreline change rate of the beach near the embankment is about –44 m/year.

3.2. Diffusion coefficient of longshore sand transport

Equation (4) is used to model the shoreline evolution with different values of ε ranging from 50 m^2/day to 220 m^2/day (Figure 11). In which, the red dots indicate the measured shoreline positions and the curves represent the modelled shoreline positions. It can be seen that the modelled shoreline with ε = 130 m^2/day show good agreement with the measured shoreline.

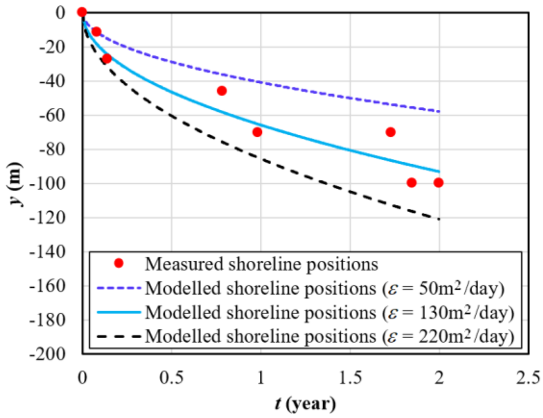


Figure 11. Modelled and observed shoreline positions

For each modelled shoreline, the RMSE between the measured shoreline and the modelled shoreline is calculated. It was found that the modelled shoreline with ε = 130 m^2/day is the best fit to the measured data (Figure 12).

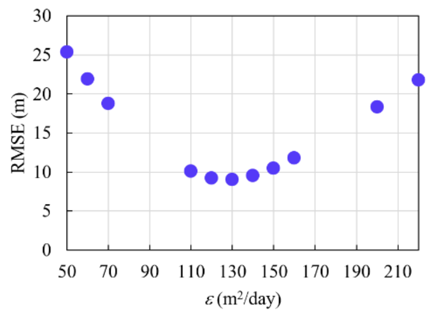


Figure 12. RMSE for each value of ε

Therefore, it can be concluded that the value of ε = 130 m^2/day is the diffusion coefficient for longshore sand transport in along the beach in Hiep Thanh commune, Duyen Hai district, Tra Vinh province, Viet Nam.

4. CONCLUSION

Remote sensing and diffusion theory have been applied to study the coastal erosion situation in Hiep Thanh commune, Duyen Hai district, Tra Vinh province, Viet Nam. The main findings of this study are as follows:

– Coastal erosion is happening at the rate of –44 m/year at the beach adjacent to the embankment.

– The diffusion coefficient for longshore sand transport due to breaking waves in Hiep Thanh commune, Duyen Hai district, Tra Vinh province, Viet Nam is $\varepsilon = 130$ m^2/day.

Caution should be exercised when interpreting the findings of this study due to the following constraints:

– Shoreline positions extracted from Sentinel-2 images in this study were not adjusted for tidal variations.

– The determination of breaking wave angles relied on wave data collected during a brief period from 02 September 2020 to 05 September 2020 and may not accurately reflect the wave conditions throughout the entire year.

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