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Spit Morphology at an Inlet in Phu Quoc Island, Vietnam

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Spit morphology at an Inlet in Phu Quoc Island, Vietnam

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Abstract: Tidal inlets with attached sand spits are a very common coastal morphology. Since the evolution of the sand spits along the coastline have greatly affected on the social-economic development of local coastal areas. However, previous studies mainly focused on the sand spits which are usually in the scales of hundred meters in width. Therefore, in this study, morphological change of a smaller and unexplored sand spit located in the west coast of Phu Quoc Island, will be investigated. It was found that there is a seasonal variation in the evolution of the sand spit at Song Tranh Inlet. The Longshore sediment transport rates (LSTR) along the spit are in the order from 10^4 to 10^5 m^3/year. LSTRs of fourteen inlets in the literature were reviewed and the LSTRs at Song Tranh Inlet are higher than half of the LSTRs along the fourteen reviewed inlets. This study aims at contributing to the growing literature on sand spit morphological changes as well as the sustainable coastal management for Phu Quoc Island which is well known as the Pearl Island of Vietnam.

Keywords: sand spit; morphological evolution; Sentinel; Phu Quoc; LSTR

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1. Introduction

Sand spit is a narrow and elongated sediment body attached to land at one side and the other ending is free in open waters [1]. The evolution of sand spits is a subject of great interest in coastal engineering since it is resulted from the complex of processes including wave transformation, tidal exchange, longshore sediment transport (LST), and river discharge [2,3]. Due to the important role of sand spits in the coastal environments around coastal bays, lagoons, and river mouths, sand spits have become the subjects of many studies in order to fully understand the spit evolution [2,4]. For example, a spit can act as a barrier to protect the mainland from extreme ocean waves during storms [5–7]. The unique and beautiful coastal landscapes of sand spit can create a big tourism attraction [8,9]. Estuaries and lagoons behind the spit are areas of high productivity in supporting human wellbeing and habitats of many ocean species [4,10]. Beside numerous advantages, a spit also causes many problems for the coastal management of tidal inlets and river mouths [11]. The development of sand spits can block the waterway, thus affecting navigability of the channel [6,12,13]. Therefore, jetties are usually constructed to stabilize the inlets or river mouths and prevent siltation by littoral materials [14–16]. However, the presence of a jetty can significantly alter the longshore sediment transport regime and cause severe erosion at the beach downdrift of the jetty [16,17].

Many publications attempted to fully understand spit evolution throught numerous study methods such as field observation, analytical solution, numerical and physical modelling as well as image analysis. For instance, Thomas et al. [18] combined the field observed data with aerial

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photographs to study the long term evolution of a sand spit which was dominated by wave direction. Hoang et al. [19] utilized the idea of spit growth model proposed by Kraus [20] to model the elongation of sand spits in Fire Inlet Island (USA) and Bedreveln (Sweden) with the assumption that the spit width is constant. Concerning the application of numerical modelling, Tanaka et al. [21] proposed a mathematical model to predict the seasonal migration of a river mouth and made discussion with measured data. Uda et al. [22] used the BG model developed based on the Bagnold's concept [23] to simulate the elongation of a sand spit under complex effects of seabed slope, waves, and tidal flow. Idealised case of spit growth was investigated using experimental method by Petersen et al. [24]. Satellite imagery analysis, among other methods, has been used intensively in studying morphological changes of sand spits at inlets [2,12,25].

Several studies on the sandpit were also carried out in Phu Quoc Island as well. Lawson et al [25] reviewed the relationship between sand spit growth rates and sand spit width for many estuaries in the world. It can be seen from the study of Lawson et al. [25] that many spits which are wider than 100 m have been investigated. Narrow spits have rarely appeared in the literature. Since the width of a sand spit directly related to its morphological change, this current study focuses on the evolution of a sand spit which is approximate to 30 m wide in Song Tranh Inlet, Phu Quoc Island, Vietnam (**Figure 1**).

Song Tranh Inlet is located on the west coast of Phu Quoc Island as shown in **Figure 1**. Phu Quoc Island became the provincial city in 2021 [26] and the main income of this city comes from tourists and its related services owing to the beautiful beaches around the island [26]. Although tourism development in coastal zone environment of the island is growing at a rapid rate in the recent years, studies on the dynamic balance of the coastlines are very limited.

In the last decades, only a few studies, both international and domestic, related to the coastal zone of Phu Quoc island can be found in the literature such as the study on coastal geomorphology and coastal erosion in Phu Quoc island [27]. According to Nam et al. [27], erosion is predominant along the west coast of the island with the erosion length is around 35 km and the erosion rate of the beach is more than 1.5 m/year. It is also found in the study of Nam et al. [27] that the beach berm height along the west coast was approximate to 1 m. In 2016, Landsat imagery was analyzed to study the shoreline change of Phu Quoc island from 1973 to 2010 using remote sensing and GIS technology [28]. The analyzing results shown that beach erosion is dominant from 1973 to 2010 in this island with the maximum erosion rate at 0.82 m/year. Recently, numerical model was used to assess the impact of infrastructure development on the balance status of the coastline in the east of the island [29]. Based on the results of computer-based assessment, the constructions of artificial island on the east coast of Phu Quoc island has changed the hydrodynamic conditions and led to significant erosion of the surrounding beaches with the rate from 6 to 6.5 m/year.

Overall, previous studies as mentioned above mainly focused on the sand spits which are usually in the scales of hundred meters in width. Therefore, morphological change of an unexplored sand spit located in the west coast of Phu Quoc Island, Vietnam will be investigated in this study.

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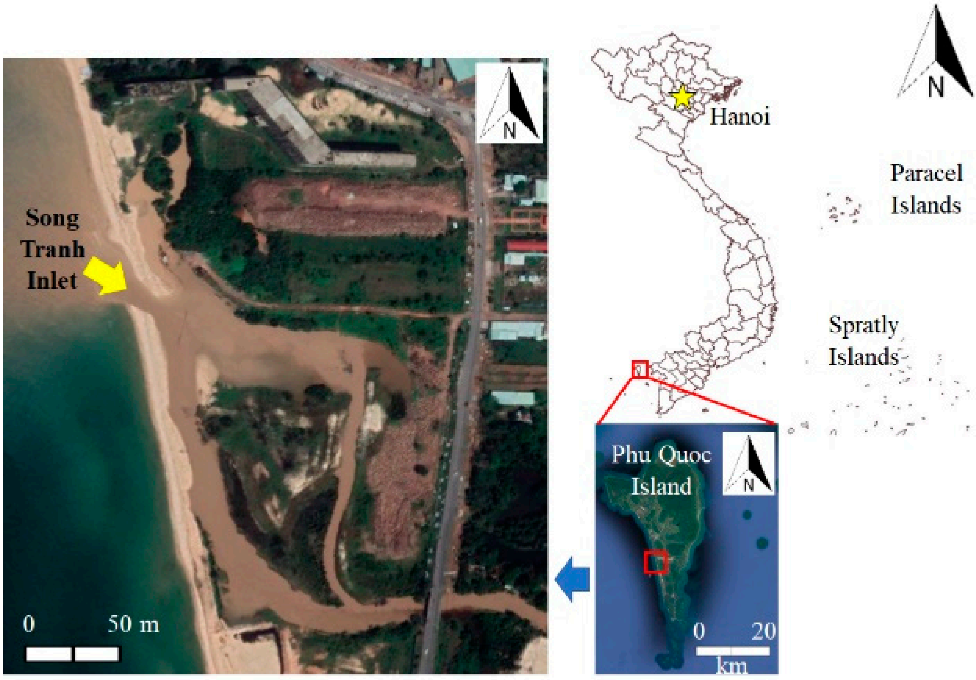

Figure 1. Location of Phu Quoc Island in Vietnam (right) and Song Tranh Inlet on the west coast of Phu Quoc Island (left).

2. Materials and Methods

Figure 2 shows the approach of this study. First, satellite images (Sentinel-2 and Google earth) and wave data were collected. Secondly, the necessary parameters for calculating the LSTR such as sand spit's elongation rate ($\Delta L/\Delta t$), sand spit's width (B), depth of closure (D_C) and berm height (D_B) will be calculated. In the third step, the LSTR will be calculated based on the idea of the one-line model. Finally, the LSTR at Song Tranh Inlet will be compared with other values in the literature.

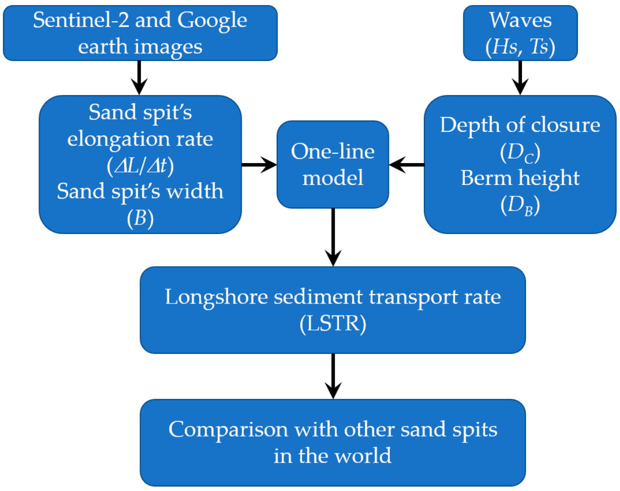

Figure 2. Flowchart of research process.

2.1. Image Analysis

2.1.1. Sentinel-2 Image Analysis

Sentinel-2 images were collected from the United States Geological Survey (USGS) to monitor the shoreline change of the sand spit on the west coast of Phu Quoc island. The satellite images were

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collected continuously for seven years from 2016 to 2022 (119 images per year). The information of sentinel-2 imagery in this study is shown in **Table 1**.

Table 1. Summary of Sentinel-2 images used in this study.

Date	Sensor	Resolution (m)	Data Source
01/08/2022	MultiSpectral Instrument	10	Sentinel-2
02/24/2022	MultiSpectral Instrument	10	Sentinel-2
03/19/2022	MultiSpectral Instrument	10	Sentinel-2
04/05/2022	MultiSpectral Instrument	10	Sentinel-2
05/13/2022	MultiSpectral Instrument	10	Sentinel-2
06/12/2022	MultiSpectral Instrument	10	Sentinel-2
07/19/2022	MultiSpectral Instrument	10	Sentinel-2
08/13/2022	MultiSpectral Instrument	10	Sentinel-2
09/17/2022	MultiSpectral Instrument	10	Sentinel-2
10/17/2022	MultiSpectral Instrument	10	Sentinel-2
11/19/2022	MultiSpectral Instrument	10	Sentinel-2
12/24/2022	MultiSpectral Instrument	10	Sentinel-2
02/06/2022	Unknown	2	Google earth
03/09/2022	Unknown	2	Google earth
08/29/2022	Unknown	2	Google earth
12/14/2022	Unknown	2	Google earth
12/19/2022	Unknown	2	Google earth
12/24/2022	Unknown	2	Google earth

The Normalized Difference Water Index (NDWI) is used to delineate the water line from the sand using the following formula [30]:

$$NDWI = \frac{X_{green} - X_{nir}}{X_{green} + X_{nir}} \quad (1)$$

where X_{green} and X_{nir} are the GREEN and NIR wavelengths, respectively.

Since the images downloaded from Google earth are not multispectral images, they will be processed using the method in the research of Pradjoko and Tanaka [31].

2.1.2. Length (L) and Width (B) of the Sand Spit

After extracting the shorelines, the length (*L*) and width (*B*) of the Song Tranh sand spit are calculated based on the geometry of the sand spit as shown in **Figure 3**. In addition, the temporal variations of the width ($\Delta B/\Delta t$) and the length ($\Delta L/\Delta t$) will be calculated using the linear regression method.

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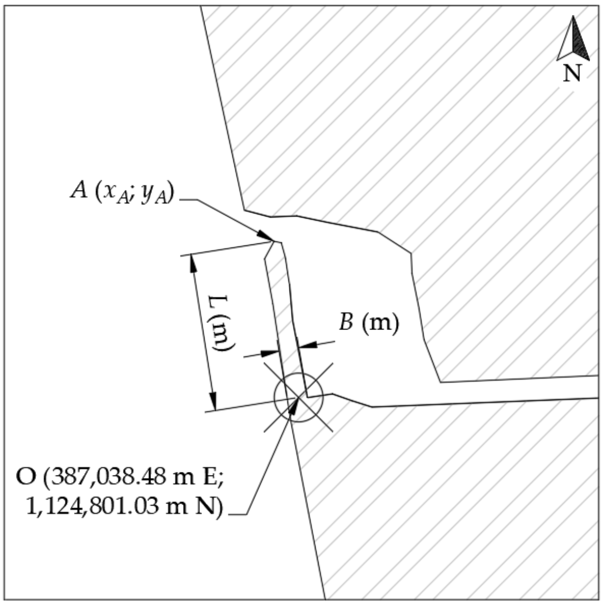

Figure 3. Definition of sand spit's length (*L*) and width (*B*) in Song Tranh Inlet.

2.2. Wave Data, Depth of Closure and Beach Berm Height

Wave data were extracted from offshore climate reanalysis data (ERA5) at location P1 (103.5^0; 10^0) and then transferred to Phu Quoc island (**Figure 4**). Wave transferring from offshore to Phu Quoc island was calculated based on the COASTEXCEL tool developed by Sana [32] and calibrated to Ocean wave data measured at Phu Quoc Oceanographic Station (**Figure 4**). **Figure 5** shows the verification of wave transferring data from ERA5 at 7:00 AM (From Jun. to Sep. 2021) in comparison with measured data at Phu Quoc station at 7:00 AM (From Jun. to Sep. 2021). There is a good agreement between the transferred and the measured wave heights (From Jun. to Sep. 2021). Therefore, offshore waves downloaded from ERA5 can be used for the analysis.

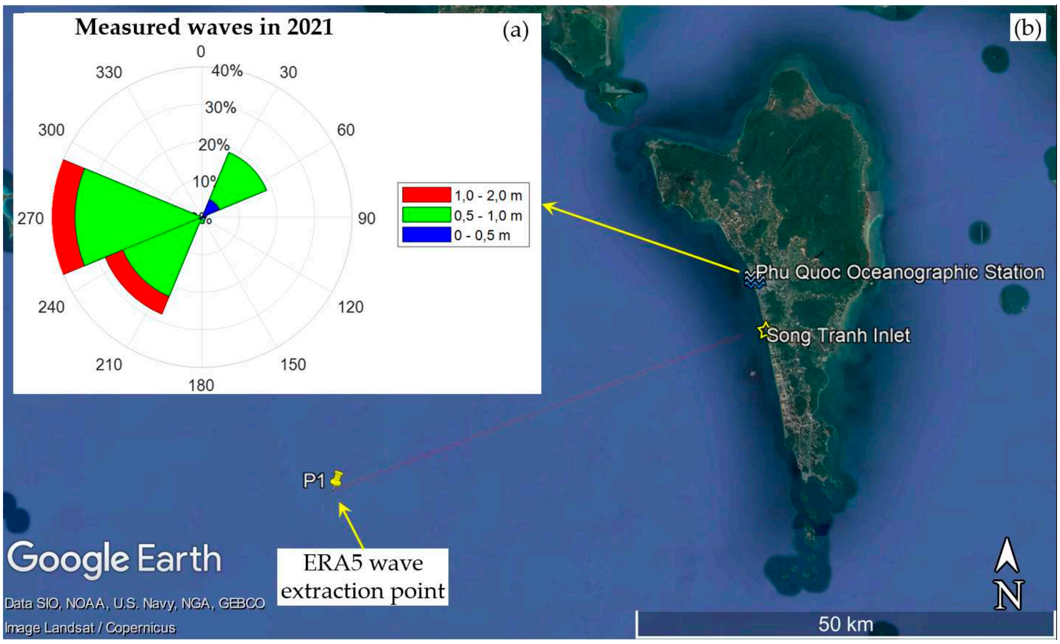

Figure 4. (**a**) Measured waves in 2021 at Phu Quoc Oceanographic Station and (**b**) Location of extracted ERA5 wave data.

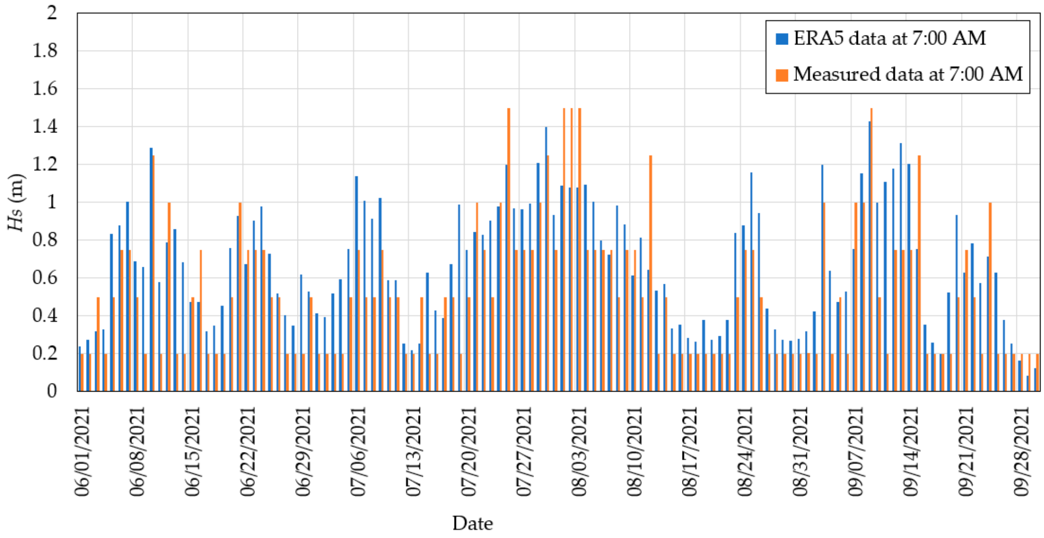

Figure 5. Wave heights from ERA5 data and measured wave heights at Phu Quoc Oceanographic Station.

The transferred waves in 2022 were used for the calculation of the beach berm height (D_B) and the depth of closure (D_C) which are two important parameters for the calculation of longshore sediment transport. The depth of closure is calculated using the equation of Hallermeier (1978) [33] as follows:

$$D_C = 2.28H_s - 68.5\left(\frac{H_s^2}{gT_s^2}\right) \tag{2}$$

where D_C is the depth of closure, H_s and T_s are the significant wave height wave period of the extreme wave condition, and g is the gravitational acceleration. According to Thomson & Harris [34], T_s should be taken to be the typical period of the measured wave height and H_s can be calculated as:

$$H_s = \overline{H} + 5.6\sigma \tag{3}$$

where $\overline{H}$ is the mean wave height and σ is the standard deviation of wave height.

A beach berm is a natural form of beach profile created by sediment transport under wave action in the swash zone. The beach berm is usually obtained by field measurement [27,35]. In the case of no measured data, the berm height can be estimated from the depth of closure using the relationship as follows [36]:

$$D_B = 0.32D_C \tag{4}$$

2.3. Sediment Samples

Since the measured waves are available at the study site, the CERC formula will be utilized for calculating the LSTR [37]. In the CERC formula, the coefficient K consistently varies with the sediment grain size (D_{50}). Therefore, five samples of sediment were taken along the sand spit to determine the D_{50} of the sediment. Locations of the sediment samples are presented in **Figure 6**. The samples were taken during a field trip to Phu Quoc Island from 20 July 2022 to 23 July 2022.

The sediment samples were then processed in the Center of Verifying and Construction Consultant of Can Tho University (https://crat.ctu.edu.vn/) to determine the (D_{50}) as well as density of the sand (ρ_s).

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Figure 6. Sediment samples were taken along the sand spit.

2.4. Long Shore Sediment Transport Rate

The results from image analysis were utilized to calculate the LSTR along the sand spit based on the theory of one-line model which was first introduced by [38] and subsequently modified for the case of sand spits [25] as presented in **Figure 7**.

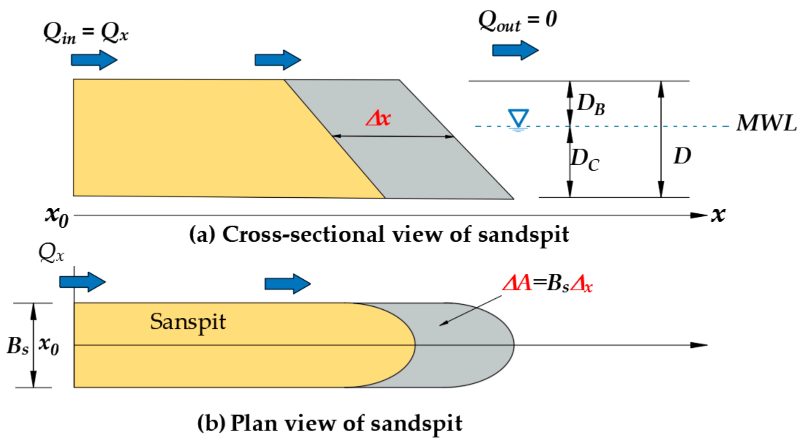

Figure 7. Proposed model for LSTR along a sand spit of Lawson et al. [25].

The model of Lawson et al. [25] assumes that, on the plan view, longshore sediment transport (Q_x) directly feeds the growth of the sand spit and there is no sediment going out at the tip of the sand spit (Q_{out} = 0). Vertically, the movement of the sand is limited in an active depth of the beach which is the total of the berm height (D_B) and the depth of closure (D_C) as depicted in **Figure 7a.** Based on the above assumption, the LSTR can be calculated as:

$$Q_x = \left(D_B + D_C\right) \times \frac{\Delta A}{\Delta t} \tag{5}$$

where ΔA is the area change of the sand spit during its elongation period Δt. Hence:

$$\frac{\Delta A}{\Delta t} = B \times \frac{\Delta L}{\Delta t} \tag{6}$$

here B is the width of the sand spit which assumed to be constant during its elongation period; $\Delta L/\Delta t$ is the elongation rate of the sand spit which can be easily determined from the image analysis.

Substituting Equation (6) into Equation (5), the LSTR can be determined as:

$$Q_x = (D_B + D_C) \times \frac{\Delta L}{\Delta t} B \tag{7}$$

Since the wave data is available at the study area, it would be useful to make a calculation of LSTR based on the wave energy. This calculated value will be used to verify the LSTR calculated using the idea of one-line model. The so-called "CERC" formula is often used to calculate the energy-based LSTR [37]:

$$Q_l = K \times \left(\frac{\rho \times \sqrt{g}}{16\kappa^{0.5} \times (\rho_s - \rho) \times (1-n)} \right) \times H_b^{5/2} \times \sin(2\alpha_b) \tag{8}$$

where K is varied with median grain size (D_{50}) of the sediment and can be calculated using the empirical relationship [39]:

$$K = 1.4e^{(-2.5D_{50})} \tag{9}$$

value of the breaker index, κ, is 0.78 for flat beach and increases due to the beach slope [40]:

$$\kappa = 0.72 + 5.6m \tag{10}$$

where m is the beach slope in the study area, here m = 0.11 for the west coast of Phu Quoc Island according to [27]. Hence, κ= 1.35. Other values for use in the LSTR formula are: ρ_s is determined from the sediment samples taken along the sand spit ρ = 1,025 kg/m^3 for salt water, g = 9.81 m/s^2 and n = 0.4; breaking wave height, H_b, and breaking angle, α_b , are taken as 0.6 m and 9^0 based on the transferred wave data from ERA5 in 2022, respectively. It should be noted that the breaking wave height used in the CERC formula is the rms wave height at breaker line and is calculated as follows [41]:

$$H_{rms} = \frac{H_s}{\sqrt{2}} \tag{11}$$

where H_s is the significant wave height:

$$H_s = \frac{1}{\frac{1}{3}N} \sum_{n=1}^{\frac{1}{3}N} H_n \tag{12}$$

where H_n represents the individual wave heights, sorted into descending order of height as n increases from 1 to N (N is the numer of waves). Only the highest one-third is used.

2.5. Comparison with Other Study Areas in the World

In this section, an equation proposed by [2] will be utilized to present the sand spit growth rate as a function of the LSTR and spit width as:

$$R_S = \frac{Q_x}{(D_B + D_C)} \frac{1}{B_S} = \alpha \frac{1}{B_S} \tag{13}$$

where R_S (m/year) is the sand spit growth rate, B_S (m) is the spit width and α (m^2/year) is the change rate coefficient.

3. Results

3.1. Temporal Variation of the Sand Spit's Shorelines through Image Analysis

3.1.1. Elongation and Breaching of the Sand Spit

Shoreline change of the sand spit in 2022 is presented in **Figure 8**. As can be seen in the figure, breaching of the sand spit occurred several times in 2022. This seasonal variation was reported as circular variation of sand spit by Weidman & Ebert [42].

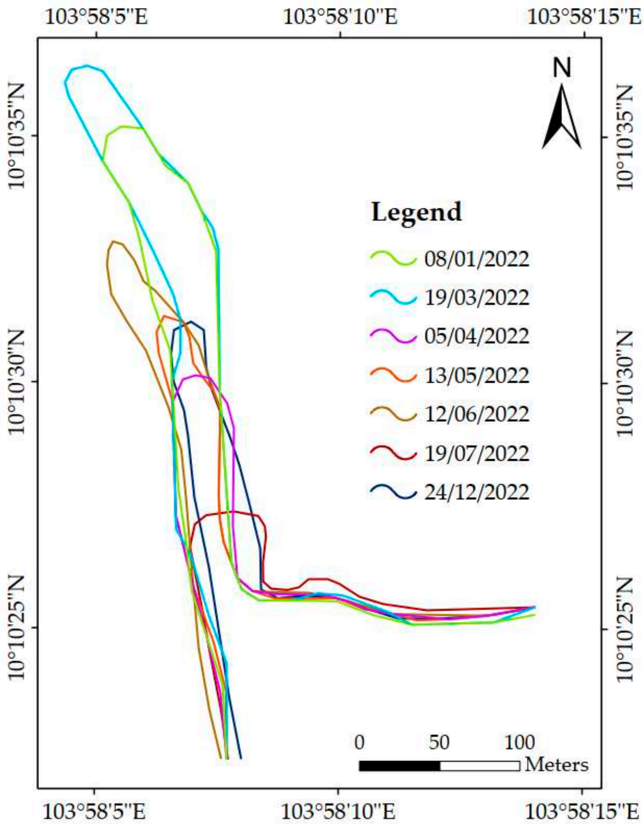

Figure 8. Temporal variation of the sand spit's shoreline.

The elongation and breaching of the sand spit in 2022 can be observed clearly in **Figure 9**. Generally, evolution of the sand spit in 2022 can be divided into three periods. The first period was from Jan. to April with the elongation rate of 0.59 m/day. At the end of the first period, breaching of the sand spit occurred around April indicating by a sudden decrease in the length (L) of the spit. After the first breaching, the second period started from Apr. to Jul. with the elogation rate approximate to 1.0 m/day. The second period ended with the second breaching occurred in Jul. In the third period, the elongation of the sand spit was 0.61 m/day.

It should be noted that the results shown in **Figure 9** are calculated from the combination of Sentinel-2 data, Google earth data, and field observation data. Although there are differences in the resolutions of the data, good agreement between the three types of data can be observed especially in period 3.

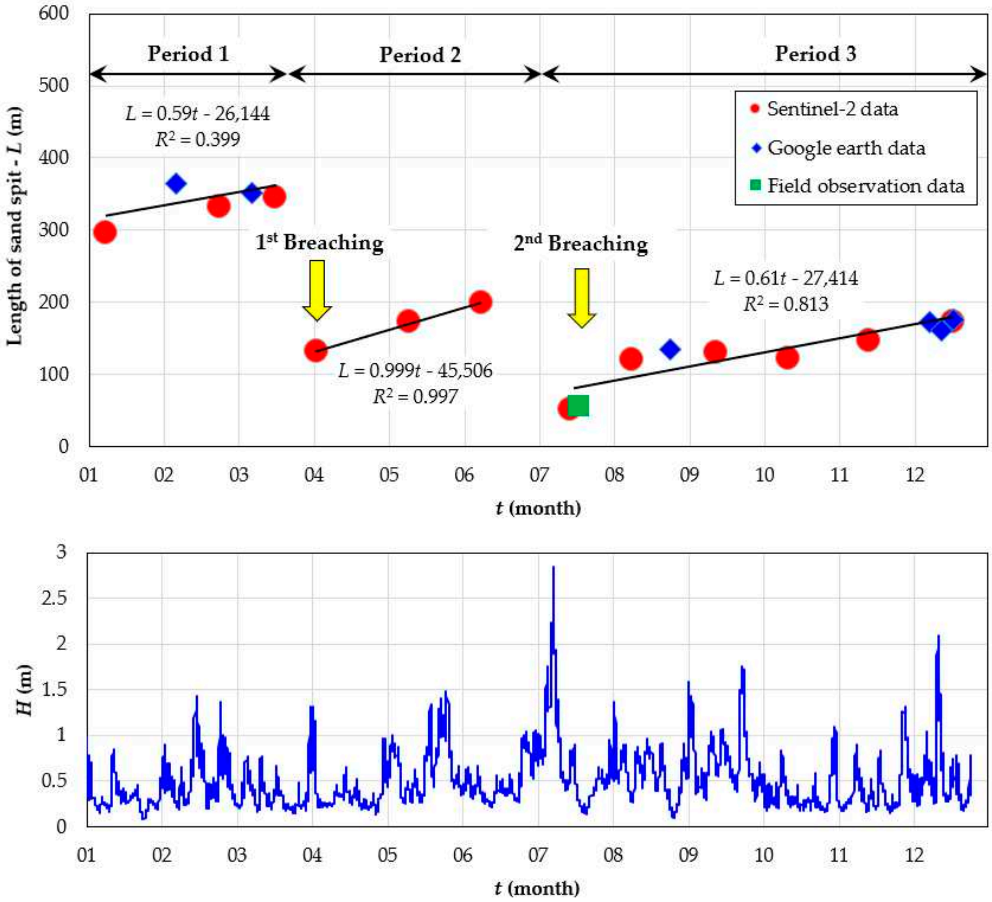

Figure 9. (**a**) Elongation and breaching of the sand spit in 2022 and (**b**) wave heights in 2022 transferred from ERA5 wave data.

Wave heights in 2022 transferred from ERA5 wave data are also presented in **Figure 9** to observe the relationship between wave action and evolution of the sand spit. It can be observed clearly that wave heights affected the breaching of the sand spit in Jul. 2022. The other breaching in Apr. may be the accumulated results of wave heights from Feb. to Apr., 2022.

3.1.2. Sand Spit's Width

It can be seen in **Figure 10** that the sand spit's width fluctuates around the value of 30 m. Therefore, it can be considered that the sand spit's width is constant during its elongation, which satisfies the assumption in the model of Lawson et al. [25].

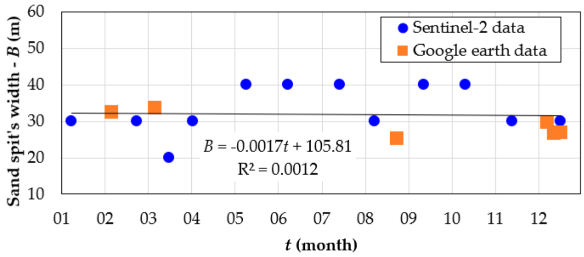

Figure 10. Temporal variation of the sand spit's width in 2022.

3.2. Depth of Closure and Beach Berm Height

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Based on the values of significant wave height and the wave period transferred from ERA5 waves, the values of D_C and D_B were obtained as 4.5 m and 1.5 m using Equations (2) and (4), respectively.

3.3. Sediment Grain Size and Sediment Density

As can be seen in **Figure 11**, the sediment grain size varies along the sand spit from 0.49 to 0.85 mm. From those values, *K* can be determined as in **Table 2**. As can be seen in **Table 2**, there is a relationship of increasing *K* with decreasing sediment size. It is also found that ρ_s = 2,775 kg/m^3 for the quartz-density sand at the study site.

Table 2. Values of *K* based on the sediment grain sizes (D_{50}).

Sample No.	D_{50} (mm)	*K*
1	0.85	0.17
2	0.50	0.40
3	0.49	0.41
5	0.58	0.33

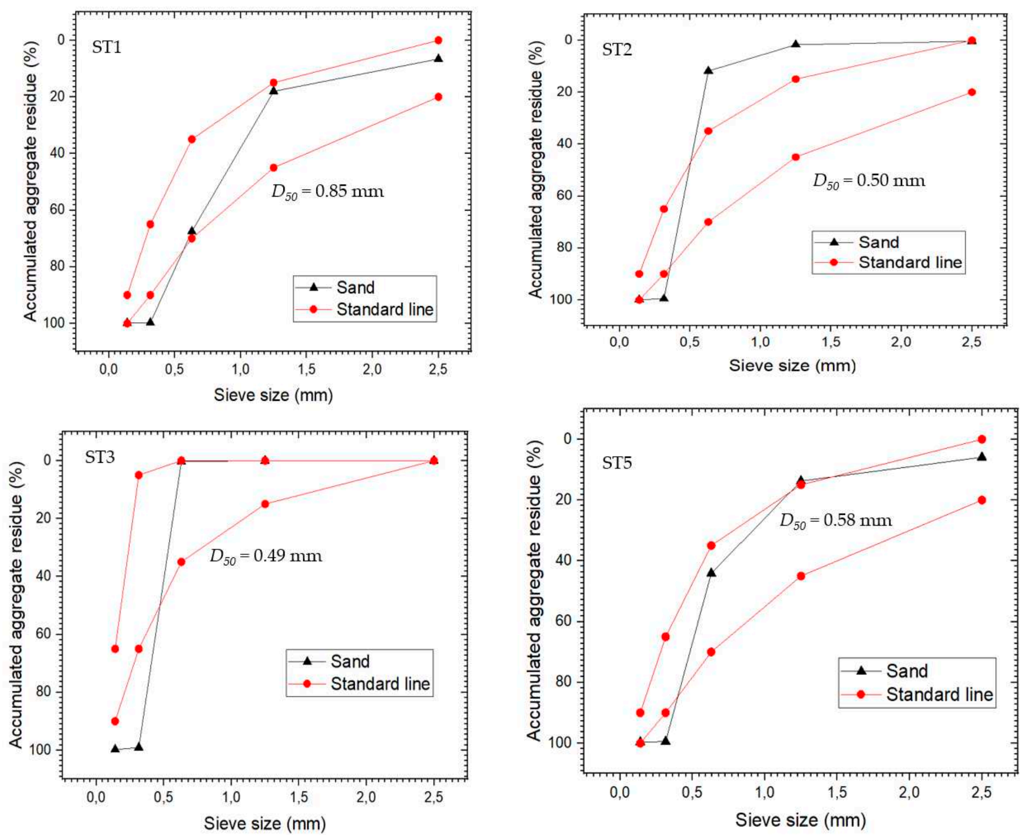

Figure 11. Sediment grain sizes along the sand spit.

3.4. Long Shore Sediment Transport Rate

As can be seen in **Figure 9**, there were three periods of the sand spit in 2022. Therefore, the LSTRs are calculated based on three periods of the sand spit in 2022. Based on the elongation rates ($\Delta L/\Delta t$) of the sand spit and Equation (7), the LSTRs in three periods are 39,000 m^3/year, 66,000 m^3/year and 40,000 m^3/year.

The wave conditions in 2022 and the sediment data (*K*, ρ_s) are used to calculate the LSTRs and verify the results from satellite image analysis. The values of LSTRs are summarized in **Table 3**. In **Table 3**, the values of LSTRs in three periods 1,2 and 3 are estimated from the image analysis while the ST1 denotes the LSTRs calculated along the sand spit using CERC formula. It can be seen that, there is a good agreement of LSTRs calculated by two methods. The variation of LSTRs and possible errors in each calculation methods will be discussed in the next section.

Table 3. Values LSTR determined based on CERC formula and image analysis.

	LSTR (m^3/s)	
CERC formula	ST1	72,000
	Period 1	39,000
Image analysis	Period 2	66,000
	Period 3	40,000

3.5. Comparison with Other Study Areas in the World

Figure 12 shows the relationship between sand spit growth rate (R_s) and sand spit width (B) at Song Tranh Inlet in three periods. The magnitudes of LSTRs are also presented by the diameters of the circles. In order to make comparison, morphodynamic properties of other inlets and river mouths in the world are plotted in the figure. Those inlets and river mouths are Volta River mouth in Ghana and Bouche du Roi inlet in Benin [25], Badreveln spit in Sweden and Fire Island Inlet in USA [19], Sangomar spit in Senegal [43] and six inlets and river mouths along the Vietnamse coastline [2,12,44,45]. All values used in **Figure 12** are summarized in **Table 4**.

Table 4. Sand spit's morphodynamic properties of other inlets.

Study Area	Country	*Rs* (m/y)	*Bs* (m)	LSTR (m^3/y)
Volta River mouth (Period 1)	Ghana	674	342	1,290,000
Volta River mouth (Period 2)		496	348	1,210,000
Bouche du Roi inlet (Period 1)	Benin	578	255	1,980,000
Bouche du Roi inlet (Period 2)		626	145	781,000
Bouche du Roi inlet (Period 4)		889	115	734,000
Badreveln spit	Sweden	28	70	10,000
Fire Island Inlet	USA	43	500	220,000
Sangomar spit	Senegal	300	124	465,000
Ken inlet	Vietnam	55	180	133,000
Ly Hoa inlet		90	130	130,000
Cua Loa inlet		50	280	160,000
An Du inlet		140	70	170,000
Phan inlet		183	60	145,000
Loc An inlet		85	150	200,000
Song Tranh inlet (Period 1)		217	30	39,000
Song Tranh inlet (Period 2)		365	30	66,000
Song Tranh inlet (Period 3)		224	30	40,000

It can be seen from **Figure 12** that the growth rates of the sand spit at Song Tranh Inlet in three periods (green, purple, and red circles) are higher than half of the fourteen data presented in the figure. The LSTRs along the sand spit at Song Tranh Inlet are also higher than six out of fourteen areas presented in the figure. With a narrow width (B = 30 m) and a high elongation rate under a high value of LSTR, it can be said that the sand spit at the Song Tranh Inlet is quite dynamic and coastal solution at this inlet is required in order to stabilize this inlet and its adjacent beaches.

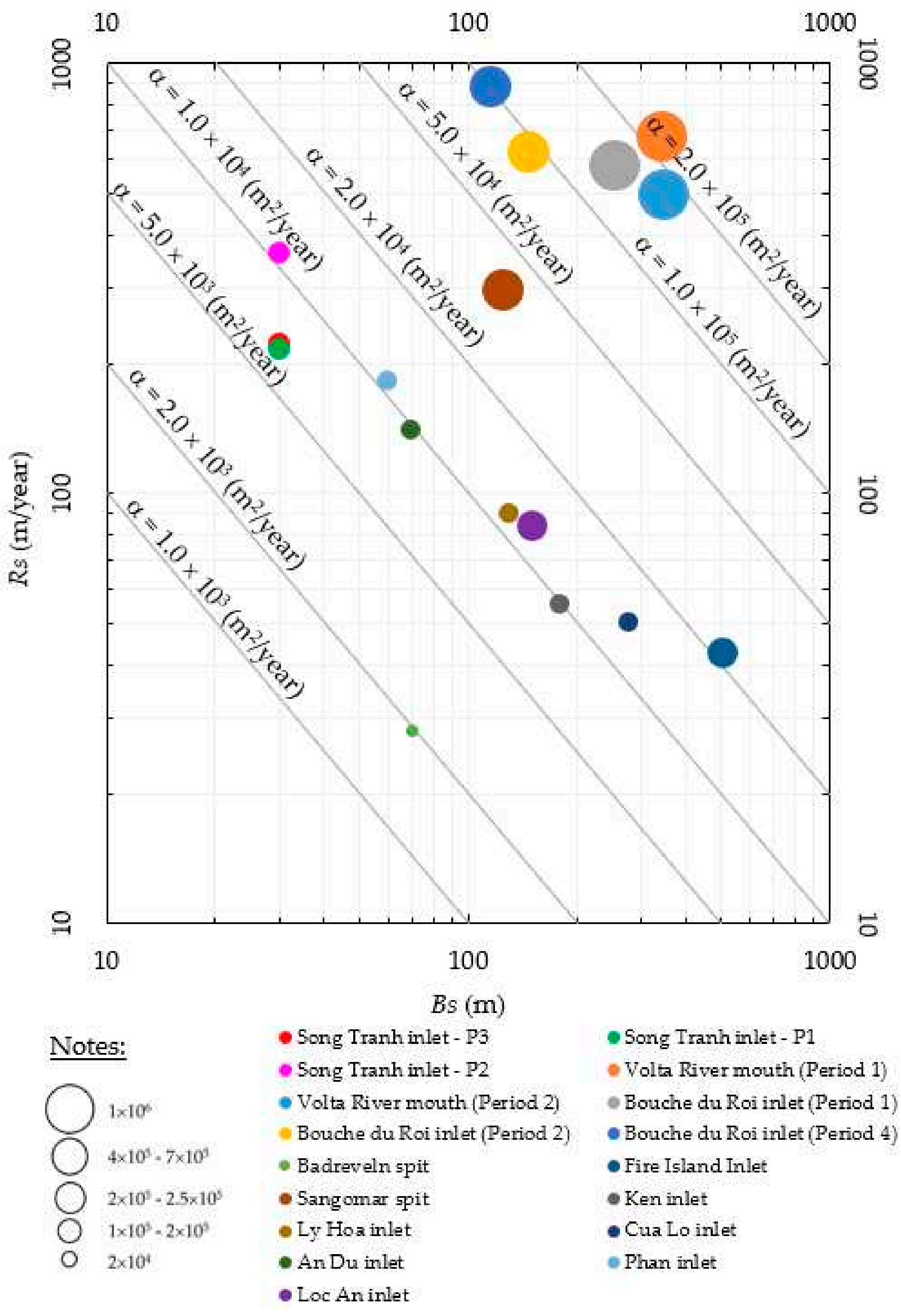

Figure 12. Relationship between sand spit growth rate and sand spit width at Tranh Inlet and other estuaries in the world.

4. Discussion

4.1. Wave Data

Although measured wave data have been obtained from the Oceanographic station of Phu Quoc Island, only wave heights and periods are available. Therefore, breaking wave angle are estimated through the refraction process using the relationship h/gT^2 with the tool developed by Sana [32]. Therefore, the breaking angle $\alpha_b = 9^0$ in this study should be used with care. In addition, the breaking

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angle always has significant effect on the LSTR [46]. Hence, this estimation of breaking angle will induce error on the values of LSTRs using the CERC formula. Improvements can be made in the following studies for this scarce data availability area by utilizing the numerical modelling as in [47].

4.2. The LSTR

Freely available remotely sensed images and the theory of one-line model have been employed to estimate the LSTR along an unexplored sand spit in Phu Quoc Island. Although most improvements of the LSTR calculation methods are nowadays implemented in relevant numerical models such as Delft-3D [48] and MIKE 21 [49], it is always nice to go back to the basics as a starting point and investigate the beach behavior [50] especially for areas under scarce data availability condition. Based on the image analysis, the LSTRs corresponds to three periods of the sand spit was quickly determined as 39,000 m^3/year; 66,000 m^3/year and 40,000 m^3/year, respectively.

In order to verify the results from image analysis, LSTR along the west coast of Phu Quoc Island was estimated based on the CERC formula. It can be seen from **Figure 13** that the LSTRs estimated in this study have the order of 10^4 m^3/year which can be considered as a good estimation for LSTR although scatter can be observed in the results [37]. The LSTRs calculated in this study using the CERC formula, without doubt, have errors due to limitation of measured data.

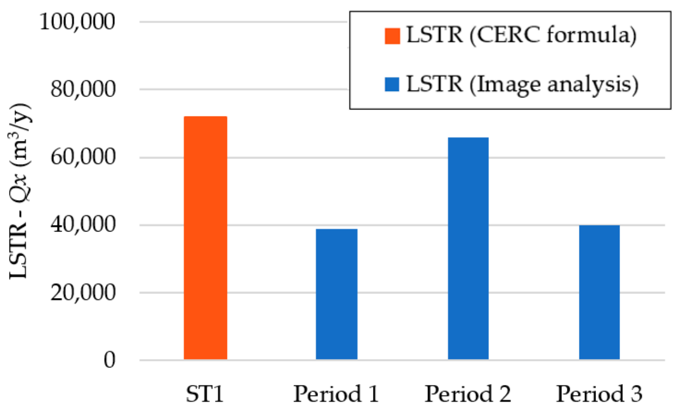

Figure 13. LSTRs estimated using CERC formula and image analysis method.

5. Conclusions

Morphological evolution of a sand spit at Song Tranh Inlet, Phu Quoc Island, Vietnam has been investigated using image analysis, one-line model and collected field data. Findings of this research could support a sustainable development of coastal area around the Song Tranh Inlet and the main findings can be summarized as follows:

- There is a seasonal variation of the sand spit in front of Song Tranh Inlet with several times of breaching and elongation in one year.
- Image analysis and one-line model were used to estimate the LSTRs along the sand spit of three periods in 2022. The results are 39,000 m^3/year; 66,000 m^3/year and 40,000 m^3/year for Period 1, 2 and 3, respectively.
- CERC formula, transferred waves and sediment data were used to calculate the LSTR along the sand spit. The calculated results was 72,000 m^3/year for the location ST1 which is in front of the inlet.
- The LSTRs calculated by two methods show the same order of magnitude.
- Fourteen values of LSTRs at inlets and river mouths around the world were revised in this study. Although the width of the sand spit at Song Tranh Inlet is the smallest one, the LSTRs at Song Tranh Inlet are higher than nearly half of the fourteen LSTRs in the literature.

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