JOURNAL OF
HYDRO-METEOROLOGY

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Research Article

Longshore sediment transport rate at a pocket beach in Phu Quoc City, Kien Giang Province, Vietnam

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Received: 12 March 2024; Accepted: 09 April 2024; Published: 25 June 2024

Abstract: This study conducts a critical examination of the Longshore Sediment Transport Rate (LSTR) along Cua Can Beach in Phu Quoc City, Kien Giang Province. This notable pocket beach is characterized by its natural beauty and burgeoning tourist developments. The escalating construction of tourist facilities and resorts in close proximity to the shoreline, without considering beach morphological changes, poses a significant threat to the coastal integrity and sustainable development of the region. In response to this concern, our research aims to estimate the LSTR on the west coast of Phu Quoc to advocate for informed coastal engineering management and sustainable development strategies. Employing an integrated methodology that combines remote sensing with a simplistic one-line model, this study provides a comprehensive assessment of sediment dynamics along Cua Can Beach. The findings reveal consistent annual sediment transport from south to north, with an estimated quantity ranging from 5,000 to 20,000 m³ per year.

Keywords: Phu Quoc; LSTR; Google earth; Satellite image; Shoreline change; One-line model.

1. Introduction

Phu Quoc, known as the "Pearl Island" for its natural beauty, is the first island city of Vietnam and a renowned tourist destination in the southwest of the country. Owing to significant socio-economic advancements over the past decade, this island city has witnessed extensive development of tourist infrastructure [1], such as resorts and bungalows, along its coastline. However, these projects have exerted considerable pressure on the coastal environment, as evidenced by several studies in recent years [2]. Although numerous studies have explored coastal engineering aspects along Phu Quoc Island's shoreline, there has been scant literature on the Longshore Sediment Transport Rate (LSTR) up to now. Given the critical importance of LSTR for coastal engineering projects and management [3–15], this study seeks to estimate the LSTR at a specific coastal cell (Cua Can Beach) on Phu Quoc Island. This estimation will provide vital data for future coastal management endeavors on the island. To estimate the LSTR along Cua Can Beach, we employed an integrated approach combining remote sensing [16] and a simplified model for shoreline change, known as the One-line model [17]. This study offers essential data, namely the LSTR, for the sustainable management of beaches on Phu Quoc Island, a key city in the southwest of Vietnam.

2. Materials and Methods

2.1. Study area

Cua Can Beach, nestled on the western shores of Phu Quoc Island, exemplifies the typical pocket beach, shaped and sustained by the sediments delivered by the Cua Can River. Phu Quoc, celebrated as Vietnam's first island city, has garnered international acclaim as a prime tourist destination, largely due to its array of pristine and enchanting beaches. Among these, Cua Can Beach stand out for its unique geographical and morphological characteristics, owed in no small part to the vital contributions of the Cua Can River. Originating from the Chua Mountain, the Cua Can River meanders through a course of 28.75 kilometers before it culminates its journey at the western sea, at the Cua Can River mouth. The river's catchment area spans an expansive 147 square kilometers, acting as a crucial source of sediments that shape the coastal landscape of Cua Can Beach [18].

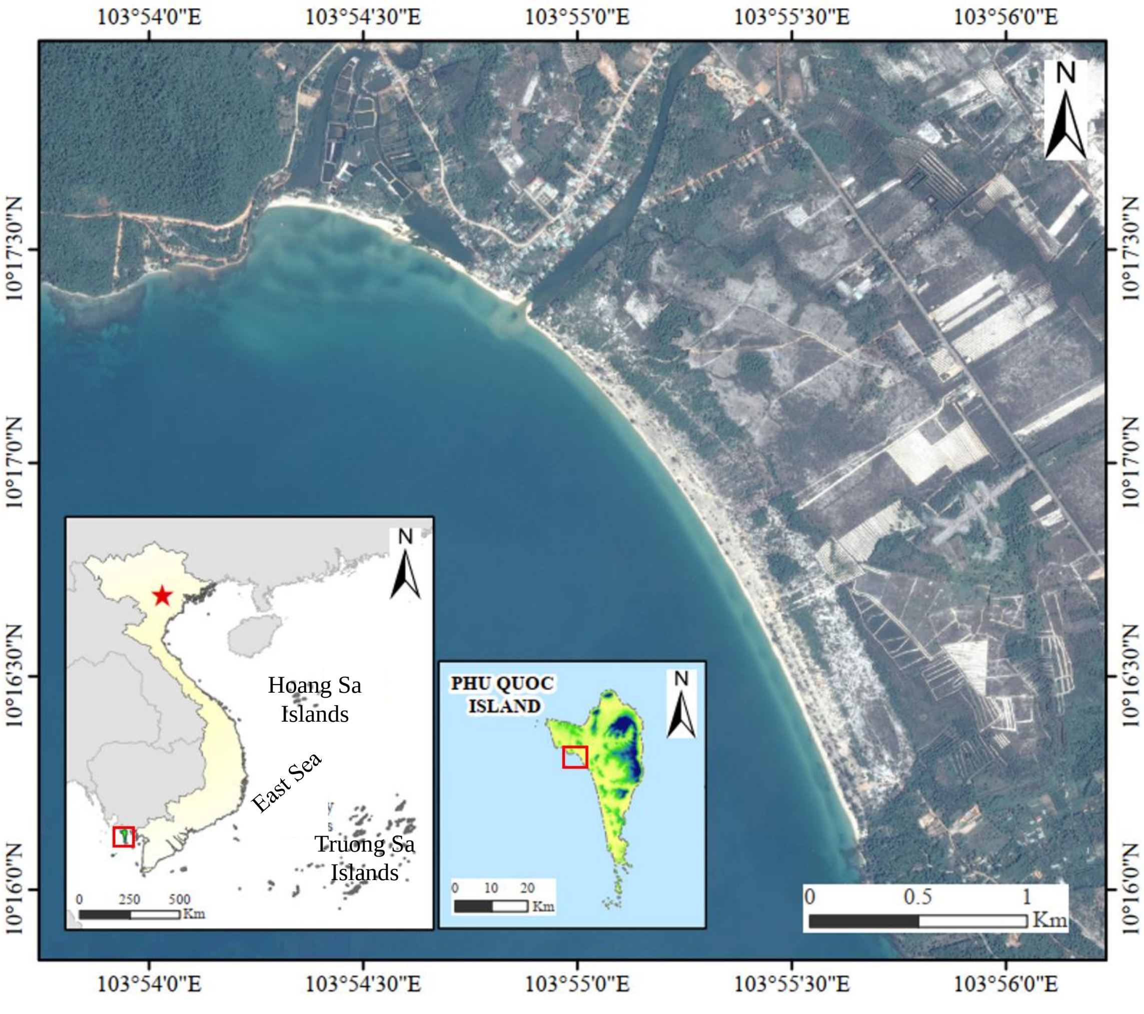

Figure 1. Study area.

2.2. Workflow of the study

The workflow of this study is illustrated in Figure 2. Initially, data collection was undertaken to acquire high-resolution Google Earth images, as well as beach slope and water level measurements. Upon gathering the necessary data, an image analysis, inclusive of tidal correction, was performed to determine the positions of the shoreline. Subsequently, changes in the shoreline and rates of these changes were statistically analyzed, utilizing the tidally corrected shoreline data. Finally, the Longshore Sediment Transport Rates (LSTR) were calculated using the one-line model, based on the determined shoreline change rates.

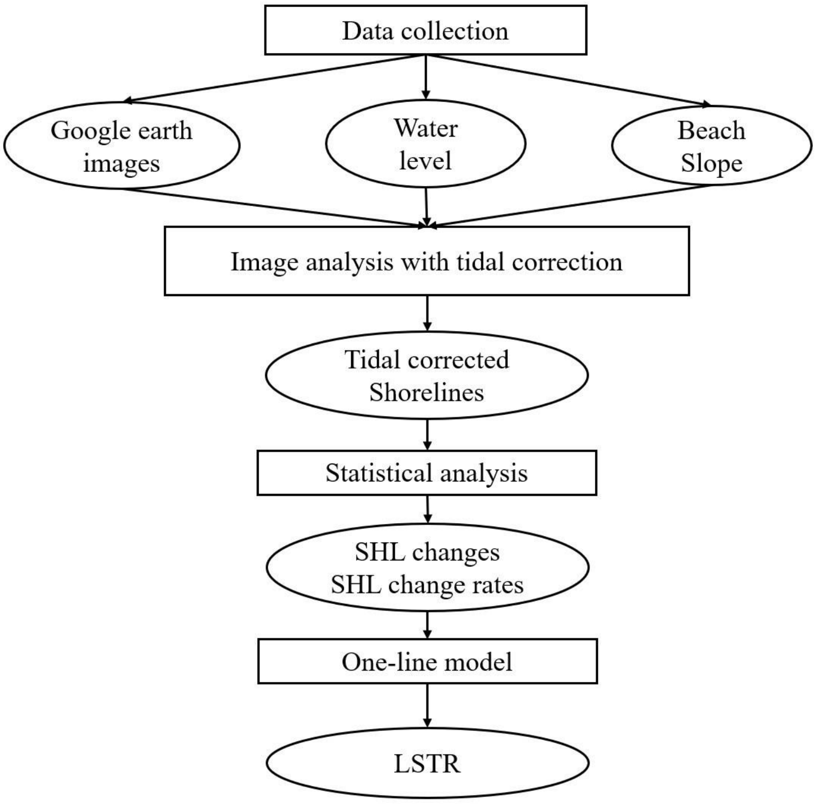

Figure 2. Study flow diagram.

2.3. Satellite image analysis

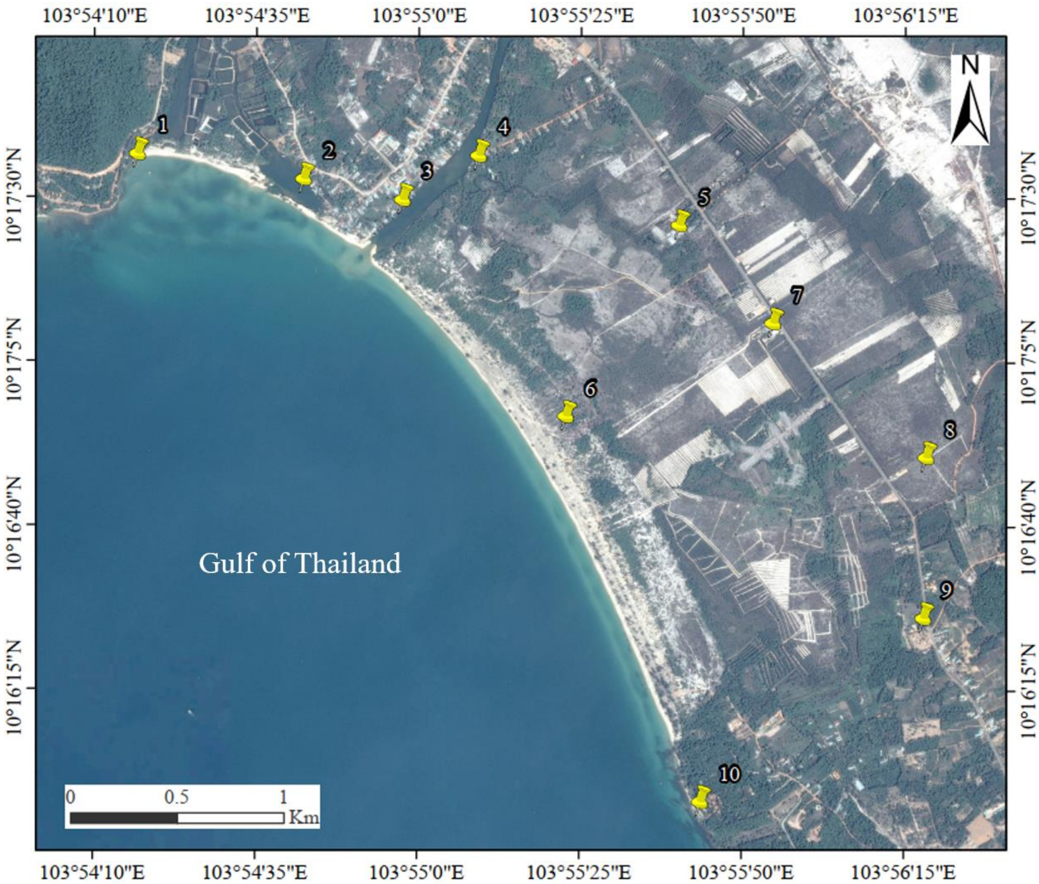

Figure 3. GCPs to geo-correct the Google earth images.

Google Earth images from 2016 to 2020 were used for the analysis. The details of the images are presented in Table 1. Since the free images downloaded from Google Earth are not geometrically corrected, they were geo-corrected using a set of 10 ground control points (GCPs), as shown in Figure 3. After geo-correction, the shoreline positions were extracted using the image segmentation approach [19]. Tidal correction was also applied to the shoreline positions using the method presented by [20], utilizing hourly water levels collected at the Phu Quoc Oceanography Station from 2016 to 2020. The water level data are presented in Figure 4.

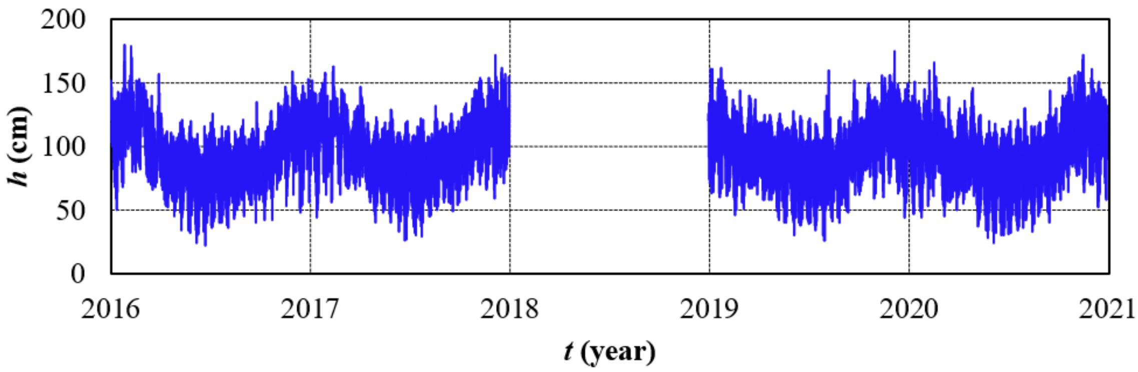

Figure 4. Water levels at Phu Quoc Oceanography station in 2016, 2017, 2019 and 2020.

Table 1. Information of Google earth images.

Captured date	Sources	Resolution (m)	Coordinate system
03 Jan 2016	CNES/Airbus	1.0 m	UTM
10 Dec 2017	Maxar Technologies	1.0 m	UTM
06 Jan 2019	CNES/Airbus	1.0 m	UTM
14 Dec 2019	Maxar Technologies	1.0 m	UTM
19 Feb 2020	Maxar Technologies	1.0 m	UTM

For the purpose of convenience, a local coordinate system was used in this study to facilite the calculation of shoreline change rates as well as integrated the LSTR a long the Cua Can Beach. This local coordinate system is defined by rotating the images in the UTM system at an angle of 132o clockwise as shown in Figure 5.

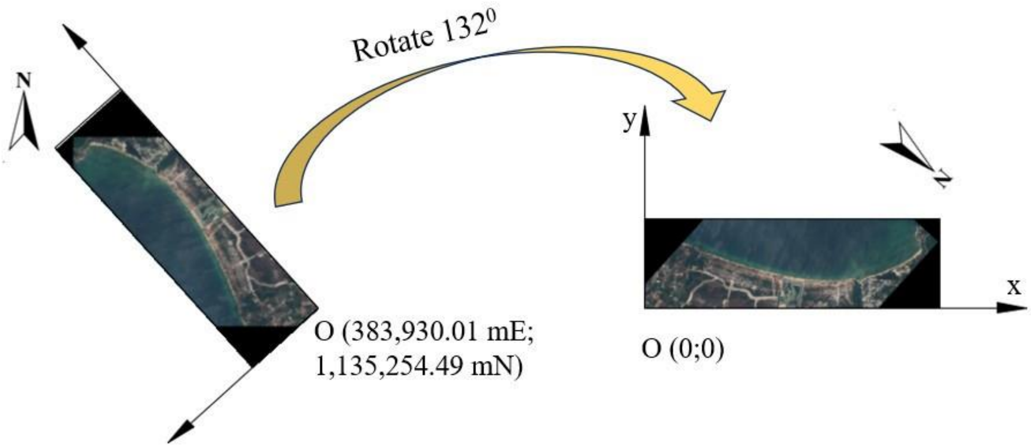

Figure 5. Defining the local coordinate system.

2.4. Shoreline changes and shoreline change rate

The shoreline positions extracted from the images were utilized to calculate the changes in the shoreline relative to the baseline established in 2016. This calculation was performed using the following equation:

$$Dy = y(x_i,t_i) - y(x_i,2016) \quad (1)$$

where $0 \le x_i \le 3800$ m and $2016 \le t_i \le 2020$.

In addition, rates of shoreline change are calculated based on the temporal variations in shoreline positions at each cross-section of the beach. This analysis employs the least squares regression method to quantify changes over time, ensuring a robust statistical foundation for understanding trends. The specific formula used for this calculation is as follows [21]:

$$y = a \times t + b \quad (2)$$

where y represents the shoreline position measured at time t, a is the rate of shoreline change calculated using the least squares regression method, and b is the intercept of the regression line with the y-axis (ordinate).

2.5. Integrated longshore sediment transport rate

The one-line theory was utilized to estimate the LSTR based on long-term shoreline changes [10]. This model states that the beach profile shifts parallel to itself in the cross-shore direction, as illustrated in Figure 7. Developed on the principle of sand conservation within a defined control volume of the shoreline section, the model presupposes the existence of both an offshore limit and an upper limit. These limits define the boundaries beyond which no significant changes occur. Within these confines, the beach profile maintains a constant shape as it moves in the cross-shore direction (Figure 7), suggesting that sediment transport gradients are uniformly distributed across the active portion of the beach [17].

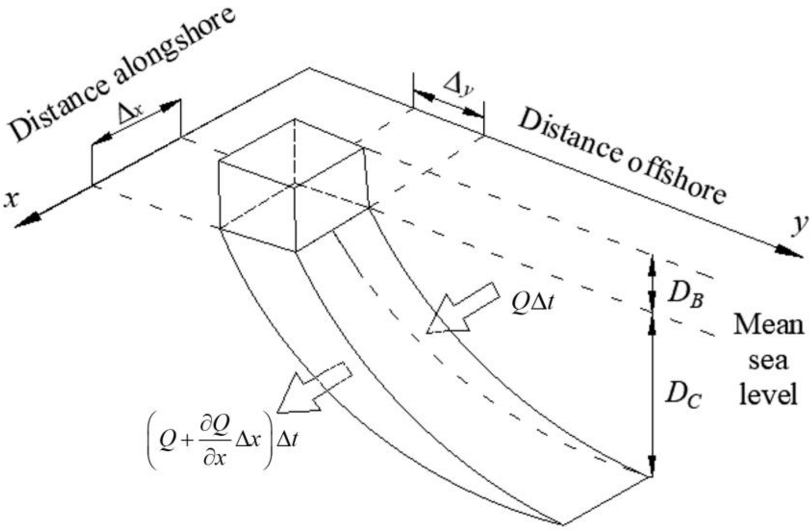

Figure 6. Sketch showing the idea of the one-line model.

The LSTR on the southern and northern coasts of Cua Can Beach were analyzed and integrated as shown in Figure 7, utilizing the theory of the One-line model. In Figure 7, the black solid lines represent the initial shoreline position, while the dashed blue lines depict the shoreline position after a period of time. This model is based on the principle of sediment conservation, which is outlined as follows [17]:

$$\frac{\partial y}{\partial t} + \frac{1}{D}\frac{\partial Q}{\partial x} = 0 \quad (3)$$

In this analysis, D represents the limit height of longshore sediment transport, which is the sum of berm height (D_B) and depth of closure (D_C), expressed as $D = D_B + D_C$. Here, t denotes time, while x and y are the longshore and cross-shore distances, respectively. Q signifies the LSTR. Due to the limited availability of measured data, the values for D_B and D_C were sourced from Song Tranh inlet, located approximately 15 km south of the study area and sharing the same coastline characteristics. As reported by [22], D_B and D_C are determined to be 4.5 m and 1.5 m, respectively, leading to a total depth (D) of 6 m.

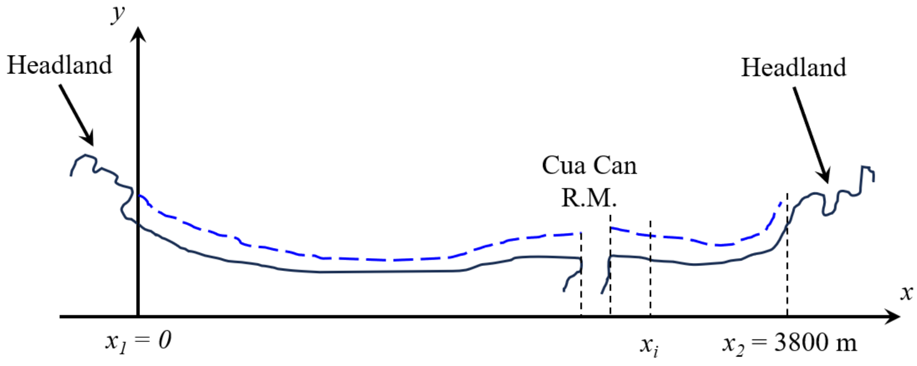

Figure 7. Integrated LSTR along the Cua Can Beach.

From Equation (3) and as illustrated in Figure 7, the integration of LSTRs on the southern and northern coasts of the Cua Can Beach area can be conducted as follows:

- For the southern coastline:

$$Q(x) = D\int_{x_1}^{x} \frac{\partial y}{\partial t} dx \tag{4}$$

- For the northern coastline:

$$Q(x) = -D\int_{x_2}^{x} \frac{\partial y}{\partial t} dx \tag{5}$$

To integrate the Longshore Sediment Transport Rates (LSTRs), it is necessary to define a boundary where the LSTR equals zero. Since Cua Can Beach is a pocket beach, the headlands at both ends are considered the boundaries where the transport rate, Q, is zero. These boundaries are denoted as $x_1 = 0$ and $x_2 = 3800$ m in Figure 7.

3. Results

3.1. Shoreline changes

Shoreline changes, with reference to the year 2016, are presented in Figure 8. As can be seen from the figure, the shoreline along the southern coast of the Cua Can River mouth remained stable from 2016 to 2020, as indicated by the fluctuations of the shoreline around the referenced line. There was a small amount of beach accumulation at the beach section from x = 1000 m to x = 1400 m. On the other hand, significant beach accretion can be observed on the northern coastline, with the maximum buildup of the shoreline approximately 35 m at the end of the beach (x = 3400 m to x = 3800 m). Another notable

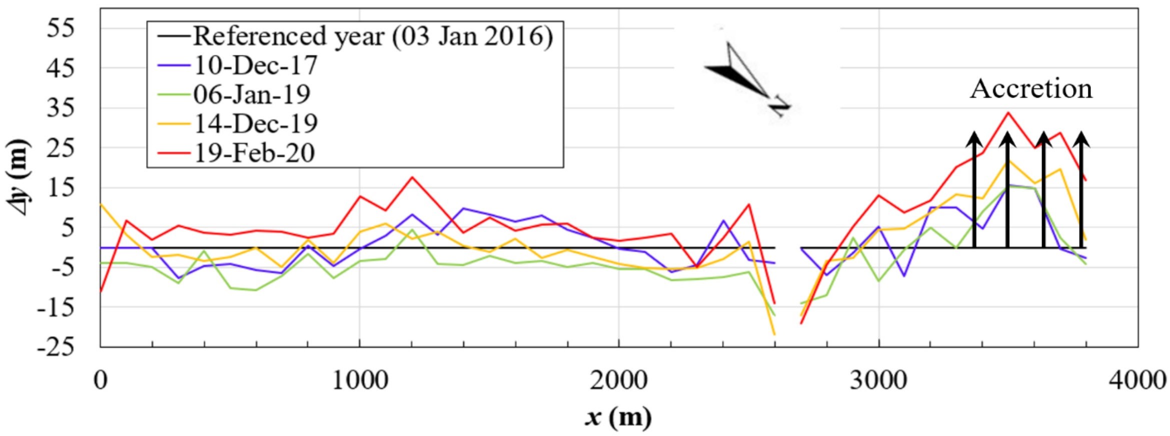

Figure 8. Shoreline changes.

point is the shoreline retreat at the Cua Can River mouth, with the maximum retreat reaching up to -25 m. From this diagram, it can be inferred that sand is being transported to the north of Cua Can Beach.

3.2. Shoreline change rates

The temporal variation of shoreline positions at selected cross-sections of Cua Can Beach is presented in Figure 9, where the blue circles represent the shoreline positions from 2016 to 2020, and the red line is the linear regression line of these positions. As shown in Figure 9, the equations of the regression lines follow the form of Equation (2). Consequently, the rate of shoreline change at each cross-section of Cua Can Beach can be easily determined from Figure 9. For instance, the rate of shoreline change at x = 2700 m is -0.0137 m/day, which equates to approximately -5 m/year. It should be noted that the results are based solely on a series of data from 2016 to 2020. Therefore, the findings of this study should be applied cautiously and must be supplemented with additional data in the future to enhance the reliability of the results. Additional calculated values for the results are presented in Table 2.

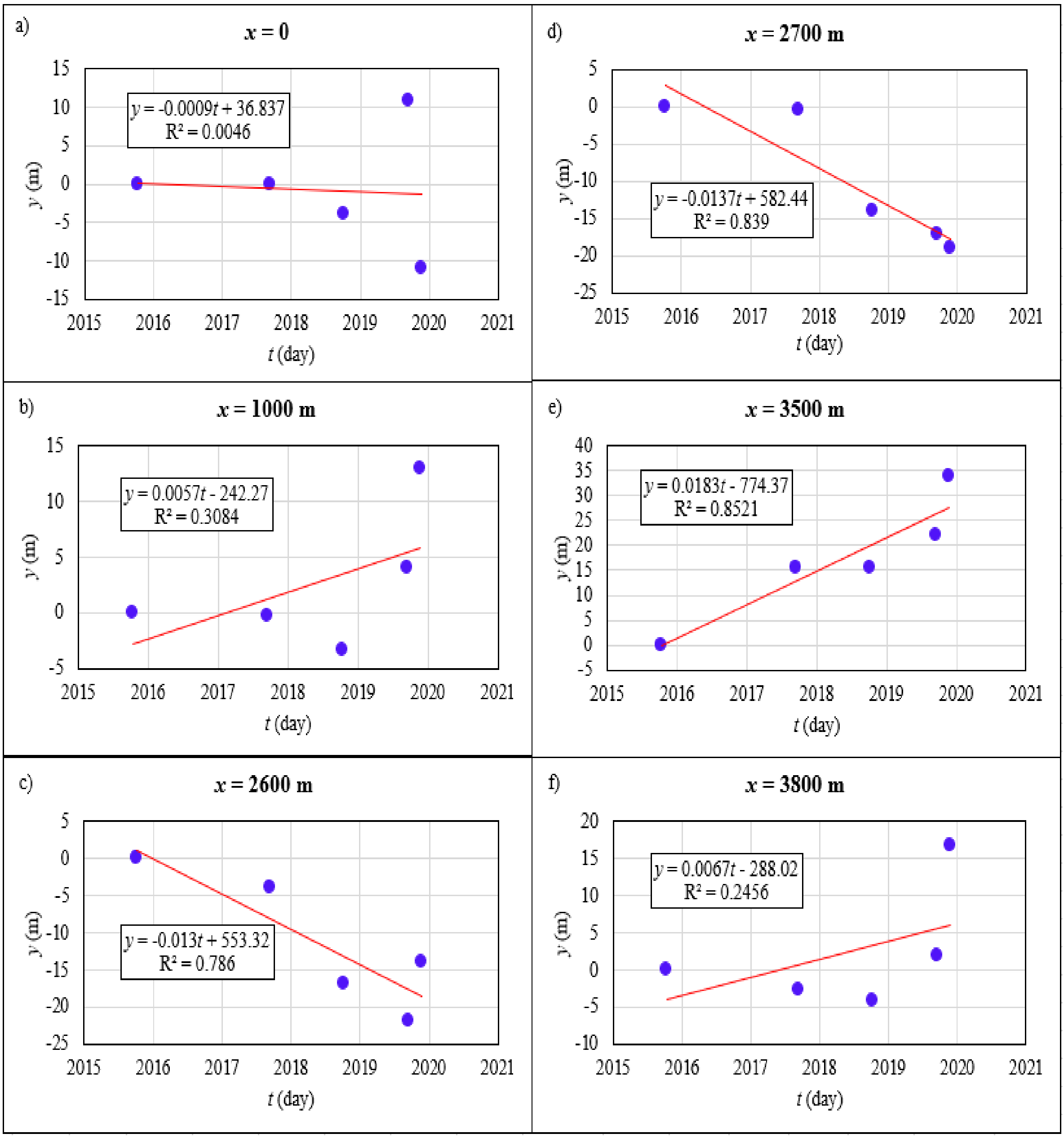

Figure 9. Temporal variations of shorelines at some cross-sections along the Cua Can Beach.

Table 2. Statistical table of additional calculated values for the results.

Cross-section	Distance alongshore x (m)	a (m/day)	a (m/year)	D = D_B + D_C (m)	DA (m^2/year)	DV (m^3/year)	Q (m^3/year)
1	0	-0.0009	-0.32	6	0	0	0
2	100	0.0031	1.13	6	40.77	245	245
3	200	-0.0006	-0.21	6	45.95	276	520
4	300	0.0017	0.61	6	19.98	120	640
5	400	0.0010	0.36	6	48.75	292	933
6	500	0.0001	0.03	6	19.43	117	1,049
7	600	0.0014	0.50	6	26.45	159	1,208
8	700	0.0002	0.07	6	28.64	172	1,380
9	800	0.0013	0.47	6	27.11	163	1,542
10	900	0.0001	0.02	6	24.54	147	1,690
11	1000	0.0057	2.06	6	104.09	625	2,314
12	1100	0.0045	1.66	6	186.11	1117	3,431
13	1200	0.0061	2.23	6	194.65	1168	4,599
14	1300	0.0043	1.56	6	189.62	1138	5,736
15	1400	-0.0005	-0.18	6	69.17	415	6,151
16	1500	0.0008	0.30	6	6.46	39	6,190
17	1600	0.0008	0.30	6	30.09	181	6,371
18	1700	-0.0003	-0.13	6	8.56	51	6,422
19	1800	0.0008	0.28	6	7.51	45	6,467
20	1900	-0.0006	-0.23	6	2.12	13	6,480
21	2000	-0.0012	-0.44	6	-33.90	-203	6,277
22	2100	-0.0011	-0.41	6	-42.74	-256	6,020
23	2200	-0.0002	-0.09	6	-25.00	-150	5,870
24	2300	-0.0035	-1.28	6	-68.25	-410	5,461
25	2400	-0.0019	-0.68	6	-97.70	-586	4,874
26	2500	0.0043	1.58	6	45.19	271	5,146
27	2600	-0.0130	-4.76	6	-158.78	-953	4,193
28	2700	-0.0137	-4.99	6	-487.50	-2925	18,130
29	2800	-0.0027	-1.00	6	-299.67	-1798	19,928
30	2900	0.0015	0.54	6	-22.98	-138	20,066
31	3000	0.0045	1.65	6	109.79	659	19,407
32	3100	0.0058	2.13	6	189.03	1134	18,273
33	3200	0.0060	2.18	6	215.39	1292	16,981
34	3300	0.0100	3.66	6	291.89	1751	15,230
35	3400	0.0126	4.61	6	413.16	2479	12,751
36	3500	0.0183	6.67	6	563.87	3383	9,367
37	3600	0.0133	4.85	6	575.83	3455	5,912
38	3700	0.0170	6.21	6	552.70	3316	2,596
39	3800	0.0067	2.45	6	432.70	2596	0

The diagram in Figure 10 depicts the rate of shoreline change along Cua Can Beach, segmented at 100 m intervals. The rate of change is visually represented by a line graph, with the horizontal axis (x) marking the distance along the beach in meters, and the vertical axis (a) indicating the rate of shoreline change in meters per year (m/year). Upward spikes along the line graph correspond to areas of accretion, while downward spikes indicate erosion.

Noticeably, there is a significant retreat at the river mouth, indicated by a rate of -5 m/year, which signifies erosion. Conversely, along the northern stretch of the beach, there is a substantial advance, with the maximum accretion rate reaching up to 6 m/year. This positive change rate indicates areas of beach growth or accretion.

The majority of the southern shoreline exhibits stability, with no discernible rate of change, marked as 0 m/year on the diagram. This suggests that these areas have neither gained nor lost significant amounts of sand over the observed period. An exception is noted in the section between 1000 m and 1400 m, where there is evidence of accretion with a change rate of up to 2 m/year.

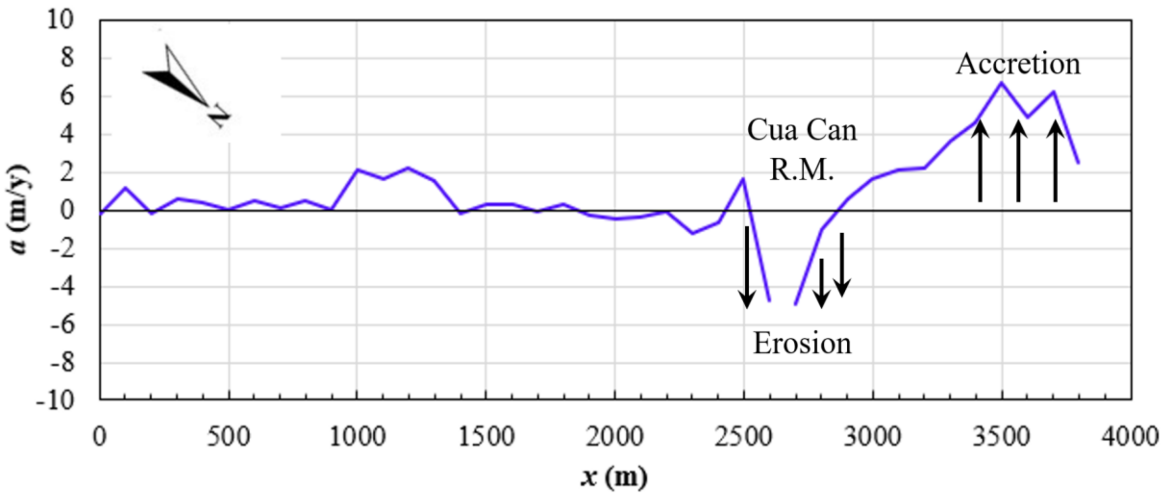

Figure 10. Shoreline change rate at intervel of 100 m along the Cua Can Beach.

3.3. LSTR along the Cua Can Beach

The Longshore Sediment Transport Rate (LSTR) along Cua Can Beach is depicted in Figure 11. The figure reveals that LSTR was substantial along the northern part of Cua Can Beach, with a rate of 20,000 m³/year. In contrast, the LSTR on the southern side of the Cua Can River mouth was much lower, at approximately 5,000 m³/year.

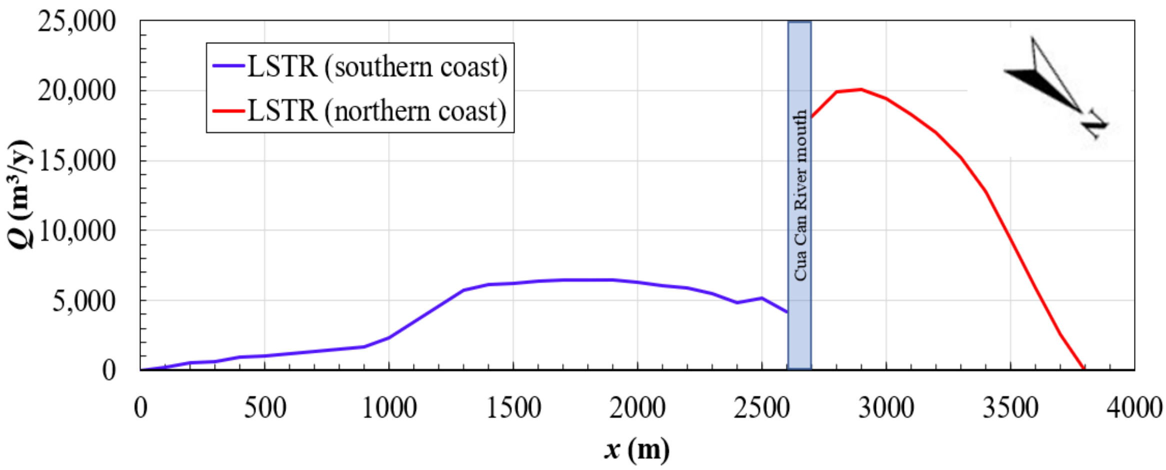

Figure 11. LSTRs along the Cua Can Beach.

4. Discussions

To evaluate the results of this study, the Longshore Sediment Transport Rate (LSTR) estimated herein was compared with LSTRs estimated for the Song Tranh Inlet [22], which is located approximately 15 km south of our study area, along the same coastline on the west coast of Phu Quoc City. This comparison is depicted in Figure 12. In the study at Song Tranh Inlet [22], the LSTR was calculated based on morphological changes of the sand spit at the inlet. The LSTR calculations were segmented into three periods, corresponding to the elongation and breaching of the sand spit. Additionally, a value of LSTR calculated using the CERC formula was also provided. As observed in the figure, the LSTR estimated at Cua Can Beach has the same order of magnitude as that in the Song Tranh Inlet study. This consistency underscores the validity of the methodology employed in our study.

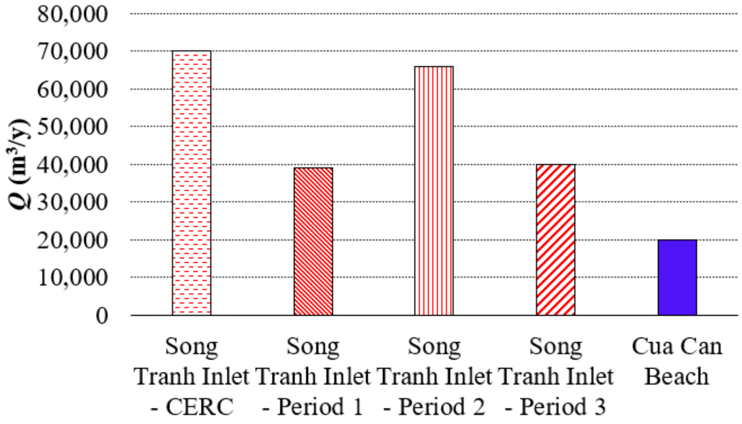

Figure 12. Comparison of LSTR with a study at Song Tranh inlet in the Phu Quoc city [22].

5. Conclusions

Remote sensing and the theory of the one-line model have been applied to rapidly assess the shoreline changes and Longshore Sediment Transport Rates (LSTRs) along Cua Can Beach in Phu Quoc City, Kien Giang Province, Vietnam, from 2016 to 2020. The main findings of this study can be summarized as follows:

- The southern part of Cua Can Beach remained stable during the survey period, while the shorelines at the Cua Can River mouth retreated at a rate of 5 m/year. In contrast, the beach on the northern part accumulated sediment at a rate of 6 m/year.
- The predominant direction of the LSTRs along Cua Can Beach was from south to north.
- The magnitude of LSTR along the southern beach was 5,000 m^3/year, and along the northern beach, it was 20,000 m^3/year. The maximum LSTR at Cua Can beach is comparable to the LSTRs estimated for the Song Tranh Inlet, located 15 km south of the study area.
- The main drawback of this study is that it is based solely on a series of data from 2016 to 2020. Therefore, the findings of this study should be applied cautiously and must be supplemented with additional data in the future to enhance the reliability of the results.

Author contribution statement: Developing research ideas: D.V.D.; Process data: processing, manuscript writing: D.V.D., T.V.T., P.T.D., T.K.M., N.A.H., Q.V.C.; GIS: P.T.D., P.T.T.D., N.A.H.; Reviewed and completed the manuscript: T.V.T., D.V.D.

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

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