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SAND SPIT MORPHOLOGICAL EVOLUTION AT TIDAL INLETS BY USING SATELLITE IMAGES ANALYSIS: TWO CASE STUDIES IN VIETNAM

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Abstract

This paper presents the long-term morphological changes of the sand spits at the Ken Inlet in Ha Tinh Province and Phan Inlet in Binh Thuan Province, Vietnam. The analysis results show that the sand spit morphology at Ken Inlet was drastically changed before the completion of the Da Bac sluice gate construction in 1992, after that the sand spit elongation rate became stable at a rate of about 68 meters per year. Meanwhile, the sand spit at Phan Inlet was breached three times during the winter months of 1990-1991, 1998-1999 and 2014-2015. Moreover, the results of remote sensing image analysis also show that after the sand spit have been breached, it continued elongating at a relatively stable rate of 170÷200 meters per year. Based on the analytical model by Kraus (1999) for predicting the sand spit elongation, the estimated long-shore sediment transport rates of Phan Inlet and Ken Inlet are 145,000 m^3/year and 133,500 m^3/year, respectively. These longshore sediment transport rates are a main contribution for the sand spit elongation in these study areas.

Keywords: sand spits; tidal Inlet; breaching; elongation; Landsat images; Google Earth images.

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1. Introduction

Sand spits often appear in many places e.g at estuaries, bay mouths and lagoons around the world, with different shapes, dimensions and dynamics [1]. Marine scientists in the world are particularly concerned about the morphological processes of the sand spits because they influence and can be related to socio-economic development such as flood control, environmental issues, saline intrusion and channel accretion [2].

The existance of sand spits at tidal inlets is typical and fairly common in a relatively low flow and catchment areas are not too large [3]. The sand spits at these estuaries are formed by the long-shore sediment accumulation, which can block the estuaries, lagoons or bays causing a lot of problems for the navigation transportsation activitites [4, 5]. In addition, excessive elongation of the sand spits at estuarine areas can badly affect drainage systems and cause more difficulties for flood control [5, 6]. However, it might be beneficial as the sandpit helps to reduce the saline intrusion into river upstream

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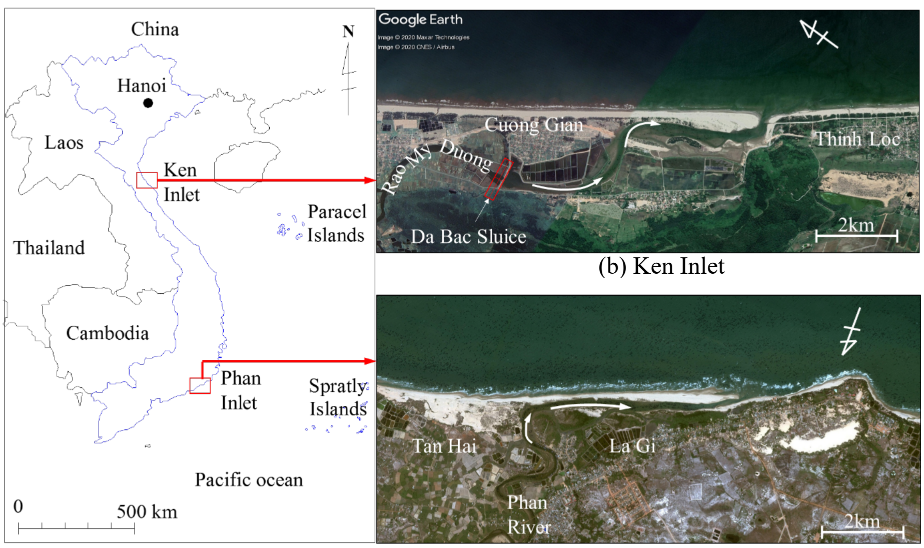
[7]. Therefore, in areas that require greater economic growth, breakwaters or jetties are often built by the inlets to estuaries to prevent sand accumulation due to the longshore drift [8–10].

In Vietnam, along with the requirements for economic development in coastal areas, large estuaries have been regularly renovated and dredged, thus the appearance of the sand spits is less common than in the past. Some typical sand spits appear at tidal inlets such as Ly Hoa Inlet (Quang Binh), An Du Inlet (Binh Dinh), An Hai and Le Thinh Inlet (Phu Yen), Ken Inlet (Ha Tinh) and Phan Inlet (Binh Thuan). The sand spits at these tidal inlets remain quite natural and their development is usually governed by natural processes. These sand spits development mostly depend on the longshore sediment transport rate, the bed materials, and hydrodynamic forcing conditions in a long-term [11]. Due to the limitation of the fulfill data in many areas, many researchers have been applied the remote sensing image analysis techniques to investigate the sand spit morphological changes [12–14]. In this study, a similar method is utilized by collecting the long-term remote sensing images to study the morphological evolution characteristics of the sand spits at two case studies: Ken Inlet (Ha Tinh) and Phan Inlet (Binh Thuan), Vietnam.

2. Materials and method

2.1. Study areas

Fig. 1 shows the location of two study areas. Ken Inlet is located in the downstream of the Rao My Duong River with a length of 15 km in Ha Tinh Province in the North of Vietnam (Fig. 1(a)). The adjacent beaches of the Ken Inlet, from Hoi Inlet to Sot Inlet, are straight, narrow, and mainly consist of fine sand. The sand spit morphology changes at Ken Inlet have changed dramatically in the past. However, after Da Bac Sluice was built in the river upstream, the sand spits in the north developed dramatically and created a relatively large area.



(a) Vietnam map

(b) Ken Inlet

(c) Phan Inlet

Figure 1. Location of study areas on Vietnam map

Phan Inlet is a mouth of the Phan River with a river length of 40 km in Binh Thuan Province in the South of Vietnam (Fig. 1(b)). The adjacent beaches of the Phan Inlet are one of the most beautiful beaches of Binh Thuan Province and very attractive places for the tourists. The length of the coastline from Tan Hai through Phan Inlet is around 15 km. Unlike other coastline of Binh Thuan Province, which is frequently affected by big waves and is seriously eroded at a rate of about 11.33 m/year, the coastaline of Tan Hai beach is frequently advanced at a rate of 5 m/year [15].

2.2. *Data collection*

In this study, all the satellite images are collected from the free satellite imagery sources such as from the USGS-NASA Landsat and MODIS as well as Google Earth. The Landsat 4-5 images and Landsat 7-8 images have a relatively resolution of 15÷30 m/pixel. However, the higher resolution images from the Google EarthTM are only 2.1 m/pixel. A large number of remote sensing images have been collected by the authors. However, the images must meet quality requirements such as a cloud cover that is less than 20%, and should not be stretched or blurred. A summary of the collected images for both study areas is shown in Table 1.

Table 1. The number of remote sensing images is collected in the research areas

Type of images	Phan Inlet	Ken Inlet	Resolution
Landsat 4, 5, 7, 8	64 images	49 images	15÷30 m/pixel
Google Earth	12 images	8 images	2.1 m/pixel

2.3. *Methodology*

a. Image rectification and shoreline extraction

Image rectification is a process of transforming information from one image into a common mapping system using a geometric transformation [16–19]. In this study, the mapping method presented in Pradjoko and Tanaka [19] was utilized. This mapping method was reported to have a maximum error up to 6 m in the rectification. This process is done by matching corresponding points from the mapping system with the same points on the image to be processed. Therefore, all collected images will be rectified under affine transformation, which is a linear mapping method that preserves points, straight lines and planes. Sets of parallel lines remain parallel after an affine transformation. The coordinate origin of these images will be established to facilitate the observation and analysis of the morphological evolution characteristics of the sand spits.

It is vital to choose a certain numbers of appropriate Ground Control Points (GCPs) which belong to the original images. It is worthwhile to note that affine transformation requires no elevation difference between selected control points. GCPs have been chosen as permanent objects or stationary features e.g. road intersections, building corners, or sea walls, etc. The best coverage for transformation process and GCPs should also be distributed evenly throughout the image in order to obtain higher accuracy of the rectified image. Table 2 shows the WGS84 coordinates of the GCPs for both Phan Inlet area and Ken Inlet area.

The positions of GCPs of Phan Inlet from P1 to P7 are shown in Fig. 2. An example of a raw image and the rectified images are presented in Figs. 3(a) and 3(b), respectively. Similar procedure has applied to all of the other collected satellite images. The shoreline position that denoted as the green color is extracted from the rectified image in the alongshore direction based on the difference in color intensity of wet and dry sand as shown in Fig. 4.

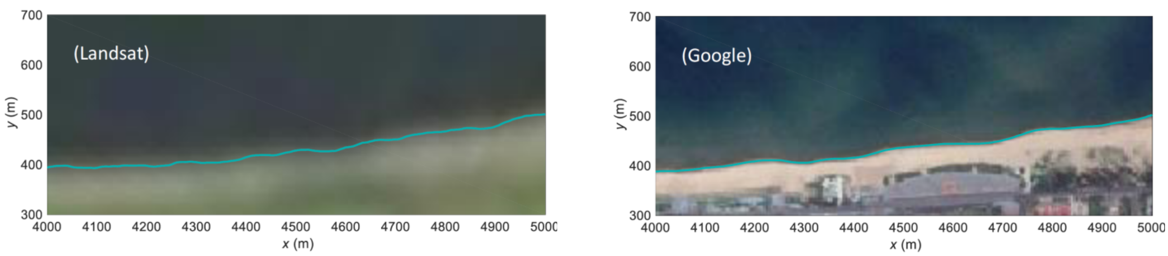
Table 2. Selection of the GCPs for Phan Inlet and Ken Intlet

Point	Phan Inlet			Ken Inlet		
	X (m)	Y (m)	Note	X (m)	Y (m)	Note
P1	1186933	817984	Ponds	2052326	589303	River bridge
P2	1186780	816824	Ponds	2051082	589053	Road intersections
P3	1186885	815459	Ponds	2050329	589698	Ponds
P4	1187209	814364	Ponds	2050136	590337	Ponds
P5	1186925	813966	Road intersections	2049151	590997	Road intersections
P6	118551	812477	Road intersections	2048348	591535	Road intersections
P7	1184939	811134	Road intersections	2052000	587749	Original Point
P8	1188035	816091	Original Point			

Figure 2. Coordinate system of rectified images and ground control points

(a) Original image (b) Rectified image

Figure 3. Transformation process

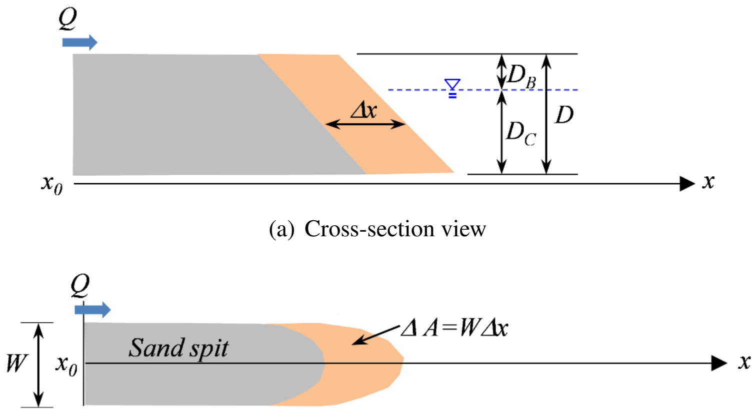


(a) on Landsat image (b) on Google Earth image

Figure 4. Detected shoreline positions

b. Longshore sediment transport rates estimation

In this study, a simple model for a sandspit elongation that similar to the method developed by [20, 21] is ultilized. The main assumptions in this model are the sand spit growth solely contributed by the gradients in longshore sediment transport (Q), the sand spit width (W) is maintains as a constant, and the spit contours move in parallel over representative time scales. Fig. 6 shows a definition sketch for sand spit elongation in a tidal inlet. In time interval Δt, the sand spit volume change ΔV equals to the newly development area of sand spit (ΔA) multiplies to the depth of active motion $D = D_B + D_C$, where D_B is the berm height and D_C is the depth of closure as seen in Fig. 5.



(a) Cross-section view

(b) Plan view

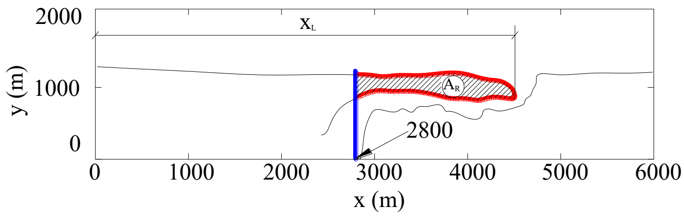
Figure 5. Definition sketch for sand spit elongation

Assumming the sand spit volume change is equal to the volume entering minus that leaving during the same time interval Δt, the sand conservation equation can be expressed as

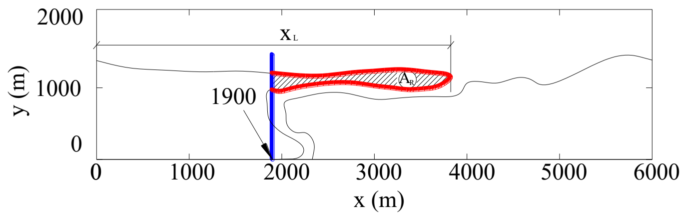
$$Q = (D_B + D_C)\frac{\Delta A}{\Delta t} \tag{1}$$

3. Results and Discussions

Fig. 6 shows the definition of the sand spit quantities such as the updrift sand spit's tip and sand spit area for investigating the morphological changes Phan Inlet and for Ken Inlet. Hereinafter, the analysis will be made based on these quantities. The analyzed results of the Phan Inlet Sand spit morphological changes are shown in Fig. 7. In these figures, the shoreline position is marked by a green line and the location of the river mouth is marked by a white arrow. Based on the results of remote sensing image analysis, the sand spit morphological evolution over 31 years can be seen. There presence of a long sand spit on the leftside of the Phan Inlet in 1988. The tip coordinate of the sand spit was located at x_L = 3,590 m (Fig. 7(a)). A first breaching was observed in 1990, the tip coordinates was retreated at x_L = 2,276 m (Fig. 7(b)). After the first breaching, the leftside sand spit was tended to elongate to the rightside and the maximum tip coordinate reached to x_L = 3,600 m in 1998 (Figs. 7(c) and 7(d)). The second breaching was occurred in 1999 and the corresponded tip coordinate was 2,014 m (Fig. 7(e)). After the second breaching, the sand spit was rapidly developed to the right over the period of 15 years. The maximum tip coordinates was observed at x_L = 3,600 m in the end of 2014 (Fig. 7(h)). The third breaching was happened in 2015, hence like the previous

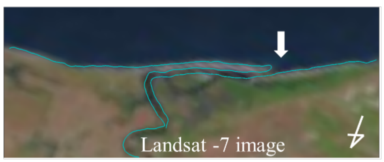


(a) Phan Inlet



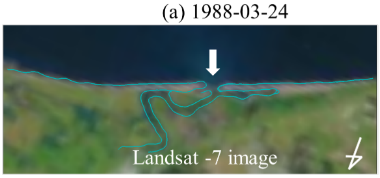
(b) Ken Inlet

Figure 6. Definitions of the sand spit quantities for investigating the morphological changes

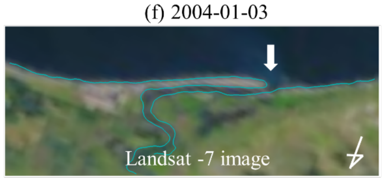


(a) 1988-03-24

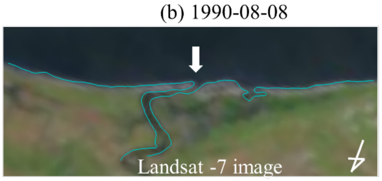
(f) 2004-01-03



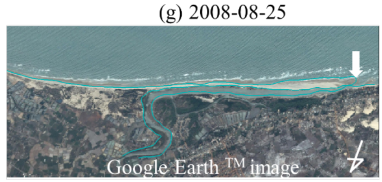
(b) 1990-08-08



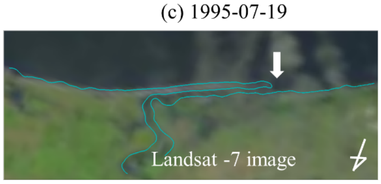
(g) 2008-08-25



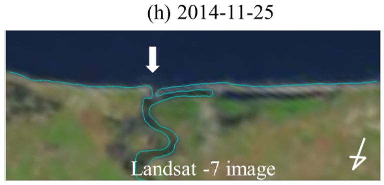
(c) 1995-07-19



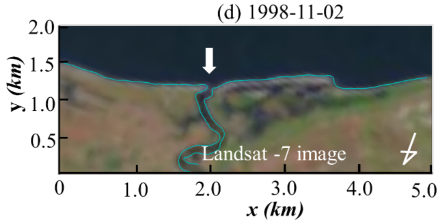
(h) 2014-11-25



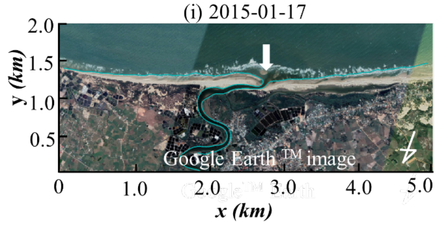
(d) 1998-11-02



(i) 2015-01-17



(e) 1999-03-26



(j) 2019-03-25

Figure 7. Morphological evolution of sand spit at Phan Inlet

cycles, the sand spit on the leftside of the Phan Inlet was again elongated to the right. The length of the sand spit increasing over 1,100 m over 4 years from 2015 to 2019 as seen in Figs. 7(i) and 7(j).

Fig. 8 shows the morphological evolution of sand spit at Ken Inlet. During the period from 1988 to 1989, it can be observed that the length of the sand spit decreased drastically (about 726 m). A new lagoon was also expanded to the right of Ken Inlet (Fig. 8(b)). The changes can be considered a result from severe river floods. After 1993, it is observed that the sand spit continuously elongated to the right of Ken Inlet for 26 years from 1993 to 2019 at a stable rate. The length of the sand spit increased considerably up to 1,640 m within 26 years, from the position of x_L = 2,870 m (in 1993) to the position of x_L = 4,510 m (in 2019) in Fig. 8(c) to Fig. 8(j). There was no breaching occurrence on the sand spit in Ken Inlet.

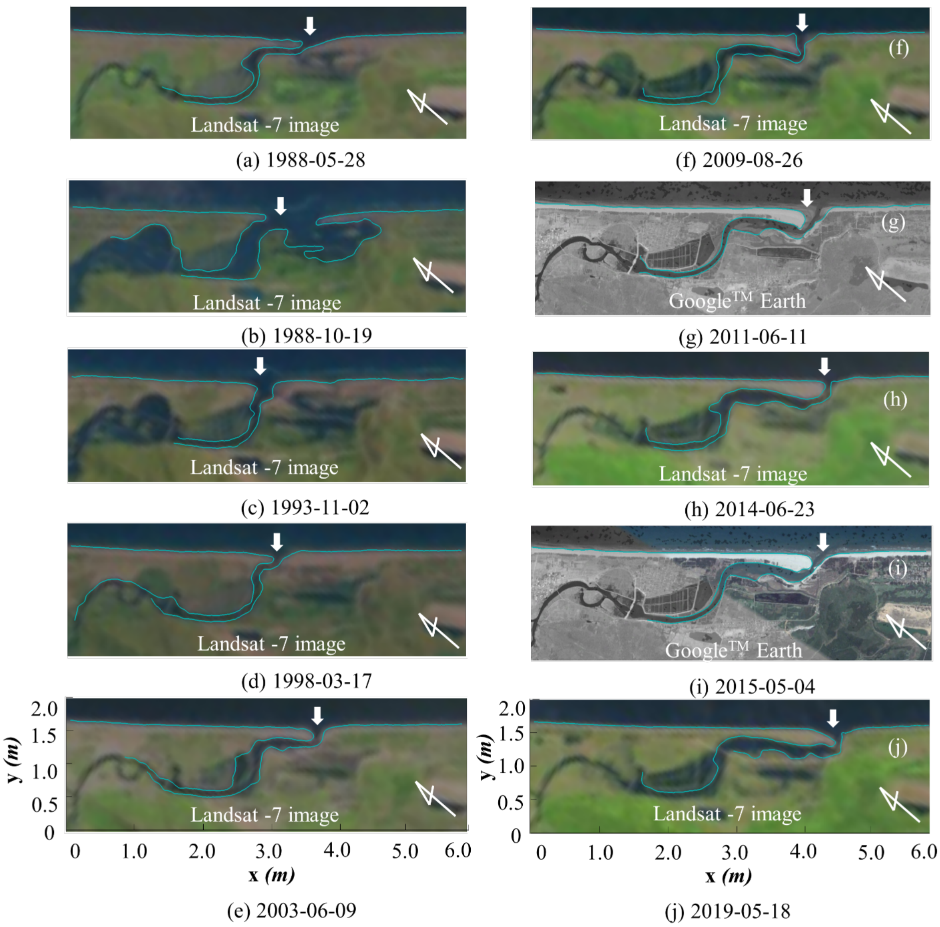


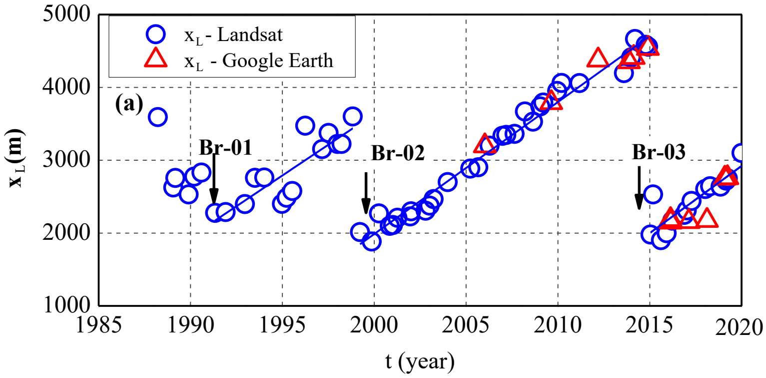
Figure 8. Morphological changes of sand spit at Ken Inlet

3.1. *Changes in the sand spit quantities of the Phan Inlet and Ken Inlet*

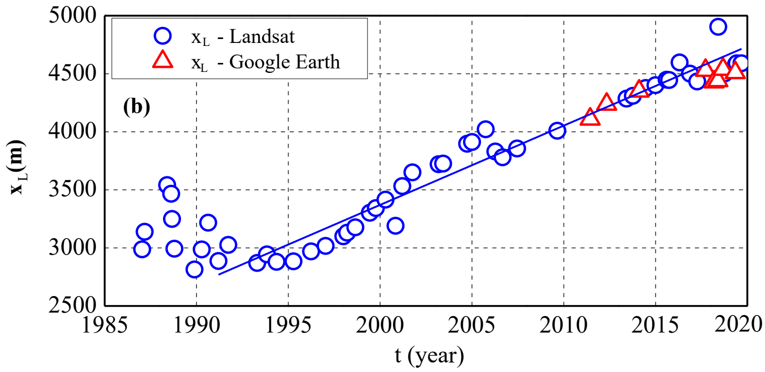
a. Sand spit elongation rates

Fig. 9 shows the analyzed results of sand spits's tip position variations for both Phan Inlet and Ken Inlet by the Landsat images (blue circle) and high quality Google Earth images (red triangle). The results show that the values of the variables analysis from the Landsat image source and Google Earth image source are relatively similar despite significant differences in image resolution.

The morphological changes of Phan Inlet are different from the Ken Inlet. The difference can be quite clearly observed in Figs. 9(a) and 9(b). Firstly, the sand spit of Phan Inlet was breached 3 times in the years of 1991, 2001 and 2015 as denoted as Br-01, Br-02 and Br-03 in Fig. 9(a). After each breaching of the sand spit at Phan Inlet, it will continue to elongate to the right at relatively similar speed. On the other hand, the sand spit of Ken Inlet was developed at a relatively stable speed in whole analyzed period. Secondly, it is evident that the sand spit elongration rate at Phan Inlet is much larger than in the Ken Inlet.



(a) Phan Inlet



(b) Ken Inlet

Figure 9. The alongshore coordinate of the updrift sand spit's tip changes at (a) at Phan Inlet (b) at Ken Inlet

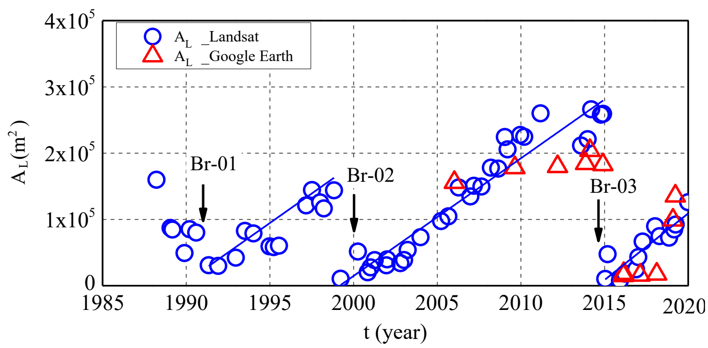
Table 3 shows the regression equations for each different sand spit growth after the breaching occurences in Phan Inlet and in Ken Inlet. The elongation rates of Phan Inlet sand spits over the three periods are 169; 181 and 201 m/year. Whereas, the elongation rate of the sand spit at Ken Inlet is 68 m/year which is much smaller than compared to the Phan Inlet case. The smaller sand spit elongation rate at the Ken Inlet was likely caused by the existence of the Da Bac sluice gate in the upstream of the Ken Inlet since 1992. This sluice gate was significantly reduced flattened the river flood flow and provide less sediment to the river mouth. While, in Phan Inlet, the flow was still in a natural conditions, so the impacts of big river floods was very significant to allow the outflow to overcome the sand spit. This may be the main reason for several breachings of the sand spits in Phan Inlet.

Table 3. Regression equations of the sand spit elongation for the Phan and Ken Inlets

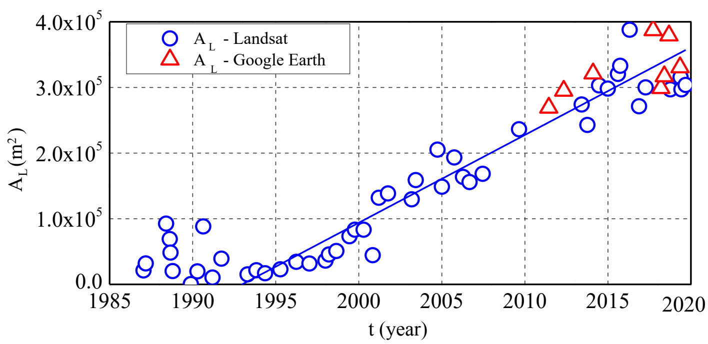
Periods	Regression equations	Correlation coefficient
3/1991 to 11/1998	$x_{L-Phan} = 168.66 \times (t - 1991) + 2{,}115 \times 10^3$	$R^2 = 0.7445$
3/1999 to 11/2014	$x_{L-Phan} = 181.04 \times (t - 1999) + 1{,}805 \times 10^3$	$R^2 = 0.9794$
1/2015 to 12/2019	$x_{L-Phan} = 201.261 \times (t - 2015) + 1{,}975 \times 10^3$	$R^2 = 0.7901$
3/1991 to 12/2019	$x_{L-Ken} = 68.2 \times (t - 1991) + 2{,}755 \times 10^3$	$R^2 = 0.8760$

b. Changing rate of the sand spit area

Similarly, the regression equations for the changing rate of the sand spit areas of Phan Inlet and Ken Inlet can also determined as shown in Fig. 10 and Table 4. The averaged changing rate of the sand spit area at Phan Inlet is about 18×10^3 m^2, whereas, it is about 13.35×10^3 m^2 for the Ken Inlet.



(a) Phan Inlet



(b) Ken Inlet

Figure 10. Changing rate of the sand spit area (a) at Phan Inlet (b) at Ken Inlet

Table 4. Regression equations of the updrift sand spit area at Phan and Ken Inlets

Periods	Regression equations	Correlation coefficient
3/1991 to 11/1998	$A_{Phan} = 14.751 \times 10^3 \times (t - 1991) + 19.624 \times 10^5$	$R^2 = 0.790$
3/1999 to 11/2014	$A_{Phan} = 17.742 \times 10^3 \times (t - 1999) - 3.053 \times 10^4$	$R^2 = 0.920$
1/2015 to 12/2019	$A_{Phan} = 21.126 \times 10^3 \times (t - 2015) + 7.038 \times 10^4$	$R^2 = 0.820$
3/1991 to 12/2019	$A_{Ken} = 13.35 \times 10^3 \times (t - 1991) - 26.495 \times 10^3$	$R^2 = 0.965$

3.2. Evaluation of the long-shore sediment transport rates

The longshore sediment transport rate can be estimated by using the Eq. (1). It is noted that the $\Delta A/\Delta t$ term is the changing rate that obtained in Table 4 for the different periods. According to Hung [22], D_B and D_C values of the Phan Inlet are 2 m and 6 m, respectively. While, D_B and D_C values of Ken Inlet are 2 m and 8 m.

Table 5 shows the estimated longshore sediment transport rates. The longshore sediment transport rates estimated at Phan Inlet in the period 1991-1998, 1999-2014, and 2015-2019 are 118,000 m^3/year; 142,000 m^3/year, and 170,000 m^3/year, respectively. Whereas, the longshore sediment transport rate of Ken Inlet is at a rate of 133,500 m^3/year.

Table 5. The longshore sediment transport rates estimation at Phan and Ken Inlets

Name of tidal inlets	Periods	Q (m^3/year)
Phan Inlet	3/1991 to 11/1998	118,000
	3/1999 to 11/2014	142,000
	1/2015 to 12/2019	170,000
Ken Inlet	3/1991 to 12/2019	133,500

4. Conclusions

This study presents the sand spit morphological changes at two typical tidal inlets in Vietnam by using the long-term remote sensing image analysis. The sand spit geometric characteristics and the elongation rate of sand spits, especially sand spits breaching phenomena for Phan Inlet in Binh Thuan province and Ken Inlet in Ha Tinh province are quantified. Sand spit elongation at Ken Inlet is at a stable rate of about 68 m/year. Whereas, the sand spit elongation rate in Phan Inlet developed very quickly with an average speed of about 185 m/year. In addition, there three breaching occurrences of the sand spit in Phan Inlet have been observed in the periods of 1990-1991, 1998-1999, and 2014-2015. The longshore sediment transport rates along the Phan Inlet were varying corresponding to each different breaching event; however, the averaged longshore sediment transport rate at Phan Inlet are estimated around 145,000 m^3/year while Ken Inlet is estimated about 133,500 m^3/year. The obtained results from this study are very useful information for the local coastal authorities to find the best management solution or plans in the future.

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