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# Historical Monitoring of Shoreline Changes in the Cua Dai Estuary, Central Vietnam Using Multi-Temporal Remote Sensing Data

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**Abstract:** Cua Dai is one of the major estuarine areas in Central Vietnam that plays a significant role in local maritime transport, fisheries, and tourism activities. This paper presents a study that monitored the shoreline dynamics of the Cua Dai estuary over a period of 50 years (1964–2014) by using field survey data, geographic information systems techniques, and multi-temporal satellite remote sensing images (ALOS-AVNIR2 and Landsat imageries). The assessment of shoreline changes was divided into three phases: 1964–1980, 1981–2000, and 2001–2014. The results revealed that over the last 50 years, shoreline changes dramatically occurred between 1964 and 1980. The general trends of erosion and accretion at the Cua Dai estuary show that the river mouth moved towards the south due to the erosion of shorelines in the north and the river bank in the south of the Cua Dai estuary. The study outcomes can provide essential information for planning, zoning, and sustainable development activities of the coastal zones in the context of climate change.

**Keywords:** shoreline changes; muti-temporal satellite remote sensing; historical monitoring

## 1. Introduction

Studies on temporal and spatial coastal shoreline changes are very important in order to establish a scientific background for disciplines such as environmental science, biology, and geography, and assist planners and policy makers in making relevant policies [1,2]. However, the shoreline is considered one of the most changeable areas in the coastal zone. Fluctuation processes are controlled by wave characteristics, beach form, sediment characteristics, and resultant near-shore circulation [3]. Assessment of the erosion and accretion of coastal areas is necessary in order to plan infrastructure systems and select the types of development for the area [2].

Shoreline changes has been analyzed using a variety of different methods and techniques which include field surveys, fixed monitoring stations, Geographic Information System (GIS), satellite remote sensing images, and transect lines techniques e.g., [1,3–9]. Field survey trips to measure the point and transect lines are usually time- and labor- consuming [4]. In addition, the field surveys using transect lines and locations are often limited in historical variation data. Therefore, an integration of multi-temporal satellite remote sensing images and field surveys would not only acquire the necessary information on the current state of shoreline changes, it would also improve the understanding of past shoreline changing processes.

A number of research studies in a variety of fields have analyzed the detection and monitoring of the shoreline by means of remote sensing images and GIS techniques. These techniques include multi-sources spatial data analysis, historical satellite remote sensing, image time-series processing, and GIS modeling [10–19]. However, there has not been any study applying the detection and monitoring of the shoreline using satellite remote sensing images as well as GIS techniques in Central Vietnam as a whole, and particularly in the Cua Dai estuary.

Vietnam has more than 3260 km of shoreline stretching over 29 provinces and 64 cities with a population accounting for more than 50% of the total national population. Quang Nam, with four districts and two cities, is a coastal province in Central Vietnam. Quang Nam has 125 km of shoreline with the two main typical tropical estuaries: Cua Dai in Hoi An city, and An Hoa in the Nui Thanh district. Both of them are endowed with valuable natural resources that are essential for coastal activities such as tourism, biodiversity conservation, marine resource exploitation, and waterway transport. However, the Cua Dai estuary of the Thu Bon River has been continuously affected by annual fluctuations, which poses a significant impact on the lives, production, and environment in the area.

With a basin of about 10,000 square kilometers, the Thu Bon River is one of nine major river systems in Vietnam. Depending on the conditions of the terrain, geology, soil characteristics, and hydrology, the flow of the river affects the erosion and accretion processes in the coastal area. Various projects at different geographic scales have been undertaken to study Cua Dai, with an aim of better understanding the effects of ocean impacts and predicting fluctuation trends to propose appropriate measures for the local economic development e.g., [9,20,21]. However, the majority of previous studies were conducted either on a relatively large geographical scale (for the entire Central Vietnam coastline) or in short periods of fluctuation time (5–10 years) e.g., [9,20–25]. Thus, an assessment of the complete picture of shoreline changes in the Cua Dai estuary, including historical trends, has not been comprehensively documented. The main objective of this study is to analyze the long-term shoreline changes of the Cua Dai estuary over a period of 50 years (1964–2014). We use multi-temporal satellite remote sensing data to investigate several potential possibilities affecting factors of erosion and accretion, and assess their fluctuation trends.

## 2. Materials and Methods

### *2.1. Study Area*

Quang Nam is located in in the south central coast of Vietnam (see location map of Quang Nam in Figure 1). It consists of 18 administrative units, which includes two cities—Hoi An and Tam Ky—and 16 districts. Overall, the province's geographical location is relatively favorable for socioeconomic development, as well as domestic and international cultural exchange.

Geologically, the coastal area of the Quang Nam province has been developed to the north central region, south central region, and Kon–Tum geological zones. The study area is located from 15°49′37″–15°55′1″ N and 108°19′1″–108°25′55″ E. In regard to climate, Quang Nam belongs to the tropical climate zone, which is affected by the cold northern wind and has only two main seasons: rainy and dry. The annual average temperature reaches 25.4 °C. The temperature of the plains may fall below 20 °C. The average rainfall ranges from 2000 to 2500 mm, but it is unevenly distributed over time and space. The rainy season mainly occurs between September and December (representing about 80% of the total annual rainfall), and rainfall in the mountain is much higher than in the plains. The rainy season also coincides with the tropical typhoon season, which often causes landslides and flash floods in mountainous and midland districts, and flooding in the plains areas.

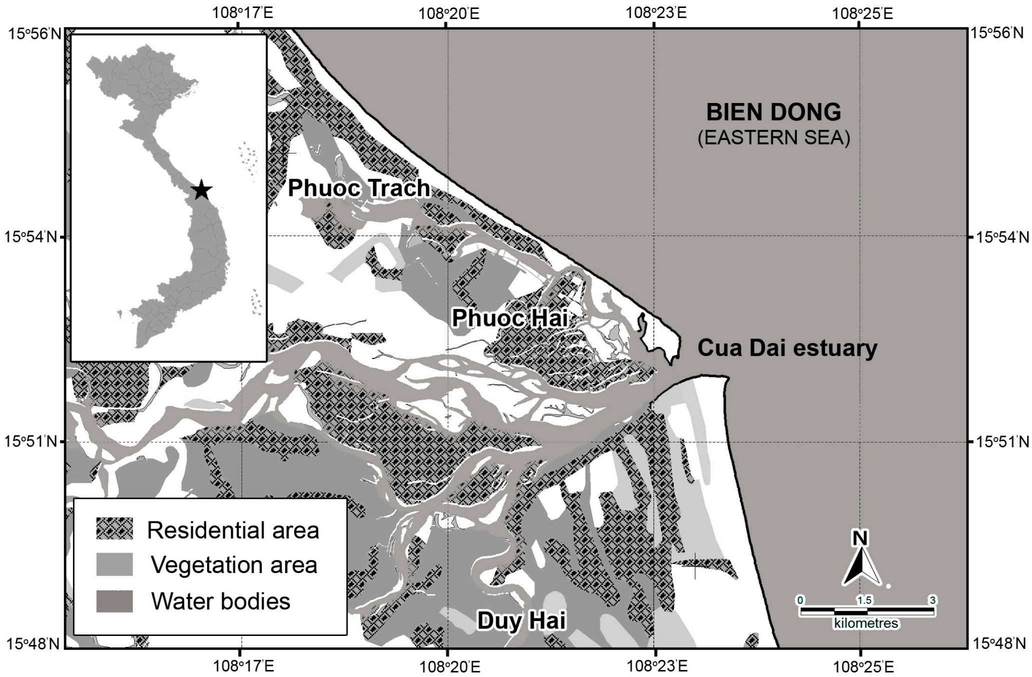



**Figure 1.** Location map of the Cua Dai estuary in Central Vietnam.

## 2.2. Materials

A number of technical and scientific reports on the status of the shoreline have been collected from previous scientific projects (KHCN 06.08). The annual and five-year reports of socioeconomic activities, planning development, and land use in Hoi An city have been documented and examined. The topographic historical map established by the US Navy meteorological office and published in June 1964 (the scene symbol HO6209) was used in shoreline assessment during the period from 1964 to 1980. The map, which was first edited in 1954 and then re-published as a second edition in 1964, covers an area from Ba Lang Cape to Tien Sa port in Da Nang city.

The temporal remote sensing satellite data including Landsat TM 5, Landsat 7 ETM+, Landsat 8 OLI and ALOS–AVNIR 2 have been employed for shoreline change assessment. The detailed information for the satellite images is presented in Table 1. The characteristics of the Cua Dai estuary morphology from multi-temporal and spatial satellite images in the selected years are illustrated in Figure 2.

**Table 1.** Characteristics of acquired multi-spatial satellite images used for the shoreline change study.

| Periods | Acquired Date * | Satellite ID | Sensors | Resolutions (m) |
|---|---|---|---|---|
| 1960–1980 | 06.1964 | U.S. Navy map | Nil | Nil |
| | 30.06.1973 | Landsat 4 | MS | 30 |
| 1981–2000 | 08.06.1988 | Landsat 4 | TM | 30 |
| | 08.01.1989 | Landsat | TM | 30 |
| | 31.12.1999 | Landsat | ETM+ | 30 |
| | 20.03.2000 | Landsat | ETM+ | 30 |
| 2001–2014 | 23.03.2001 | Landsat 7 | ETM+ | 30 |
| | 28.02.2004 | Landsat | TM | 30 |
| | 16.03.2007 | Landsat 5 | TM | 30 |
| | 11.03.2009 | ALOS/JAXA | AVNIR2 | 10 |
| | 12.04.2010 | ALOS/JAXA | AVNIR2 | 10 |
| | 25.07.2011 | Landsat 7 | ETM+ | 30 |
| | 19.03.2014 | Landsat 8 | OLI/TIRS | 30 |

* Acquired date format: dd.mm.yyyy. All satellite images were registered as map projection L1: UTM, datum: WGS 84; UTM Zone: 49N

The daily wind data (2007–2008) in 0.5–degree increments were acquired from http://poet.jpl.nasa.gov and used for assessing the distribution pattern and movement of the wind field off the Central Vietnam waters. The historical hurricane data were downloaded from the Historical Hurricane Tracking Systems of the National Oceanic and Atmospheric Administration, which is available from http://coast.noaa.gov/hurricanes/.

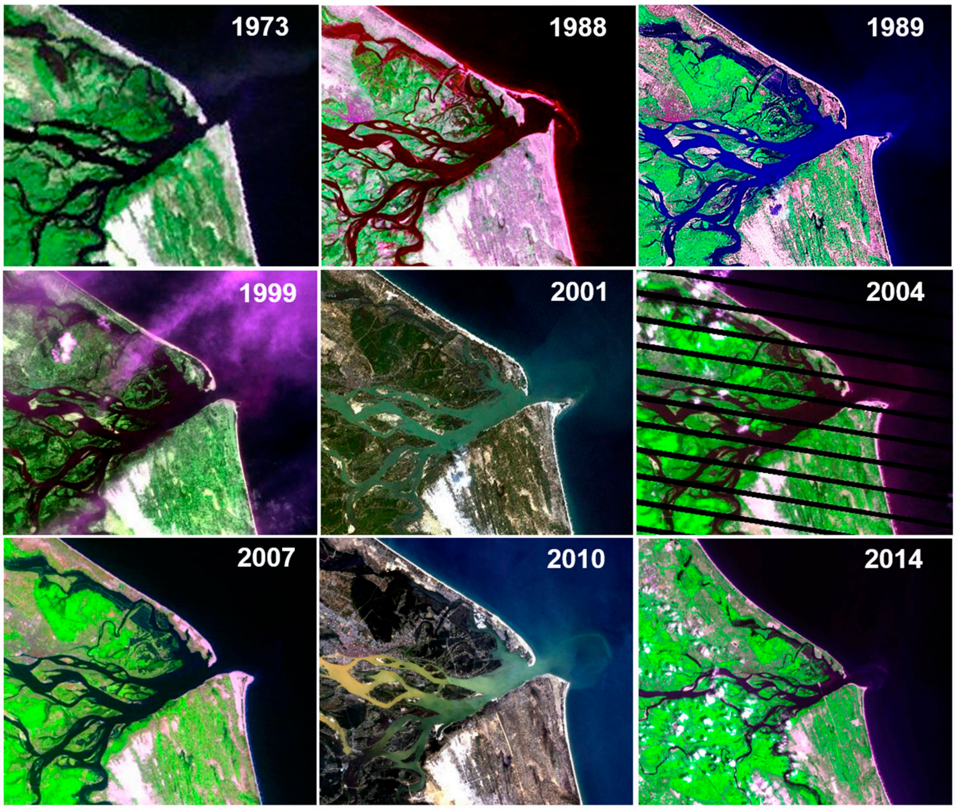



**Figure 2.** Characteristics of the Cua Dai estuary morphology from multi-temporal and spatial satellite images in the selected years.

## *2.3. Methods*

### 2.3.1. Field Survey

Two field survey trips were carried out along the Cua Dai estuary in July and November 2011. Most of the erosion, accretion, and other vulnerable areas were identified and documented using digital photos from field surveys. Ground Control Points (GCPs) at river intersections, branches, and permanent landmarks were collected for geo-referenced and satellite remote sensing classification points.

We utilized multi-temporal Landsat data and a shoreline extraction algorithm to define the shoreline in different periods. The actual shorelines were verified during the field surveys in 2011. In fact, even though the field data were limited to validate the historical remote sensing data, they were meaningful in determining accretion and erosion areas in the Cua Dai estuary.

Primary and secondary information were collected through the Participatory Rapid Appraisal (PRA) approach, which consists of semi-structured interviews, historical lines, resource mappings, rankings, and focus group discussion to obtain the status of the shoreline, socioeconomic activities, and natural disasters that have affected shoreline changes and livelihoods in the study area.

#### 2.3.2. Shoreline Detection Based on Satellite Remote Sensing Data

We standardized the images based on collected ground-truthing points and utilized algorithms of remote sensing in ArcGIS to retrieve data on shoreline changes. Satellite remote sensing images in different periods were used to retrieve and analyze the shoreline data after geometric correction and georeference.

The combination of threshold values and band rate was employed to assess the shoreline changes in this study. The equations for shoreline detecting (B3 + B4)/B1 and (B5 + B7)/B2 were used for Landsat MSS, Landsat TM, and Landsat ETM+ imageries, respectively. GCPs were acquired from less dynamic landmarks for geometric correction control points. VN2000 georeferenced at six degrees and 108°30′ longtitude were utilized for geometric processes in the baseline maps.

An affine algorithm in the GIS was used for georeferencing all input maps, with approximately 30–40 control points per map layer. The affine algorithm was described by the equation below:

$$x' = \mathrm{A}x + \mathrm{B}y + \mathrm{C} \tag{1}$$

$$y' = \mathrm{D}x + \mathrm{E}y + \mathrm{F} \tag{2}$$

where $x$, $y$ are the coordinates of the input maps; and $x'$, $y'$ are the coordinates of target maps after correction. A, B, C, D, E and F are the values calculated by comparing the control coordinates from both map layers. Then, the satellite remote sensing data were converted from remote sensing software into the GIS package. The shoreline was visibly digitized on-screen using practical knowledge, and these layers were overlaid for the analysis of changes.

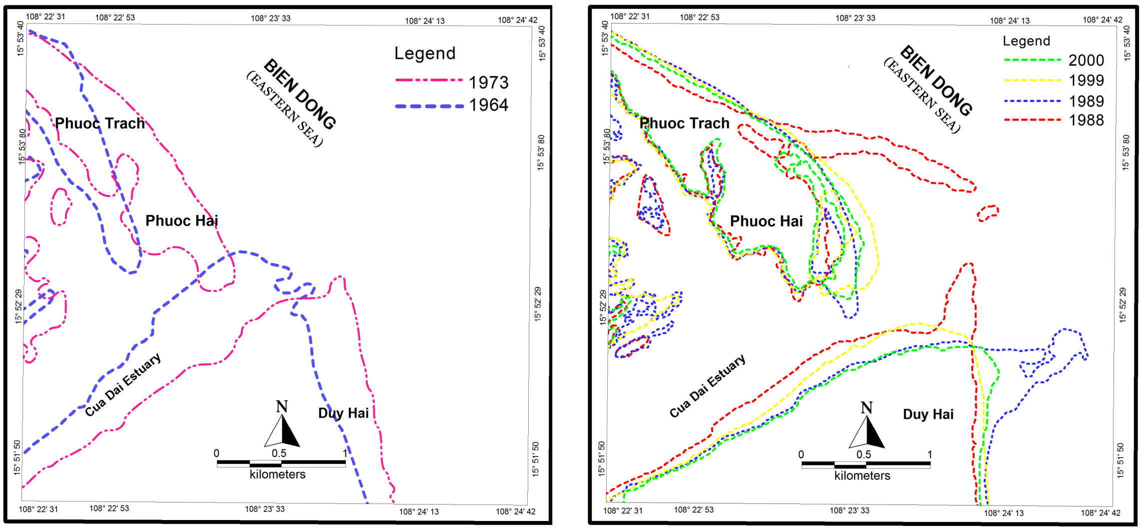
## 3. Results

### *3.1. Shoreline Changes of the Cua Dai Estuary, 1964–1980*

This phase was evaluated with limited historical maps and remote sensing images data. The latest topographic historical maps established by the US Navy, which cover the area from Ba Lang Cape to Tien Sa port, Da Nang, and Landsat 1 images on June 30, 1973 were used for the assessment of shoreline changes in the Cua Dai estuary. The analysis results showed that there was a significant fluctuation in this phase. The north of the Cua Dai estuary and the adjacent shoreline accreted forming a large peninsula and moving the cape in a southerly direction by about 380 m as compared to its location in 1964. The eastern part of the Cua Dai accreted around 330 m, and in some areas, up to 570 m, in comparison with the 1964 shoreline.

In the south of the Cua Dai estuary, the shift from the northern river mouth to the southern side was relatively large. On the south bank of the Cua Dai estuary, the shoreline increased by 250 to 390 m in 1973 compared with the 1965 shorelines. The largest position in the seaside shifted by about 510 m (Figure 3a). Meanwhile, the banks of the adjacent shoreline areas in the Duy Hai commune accreted and shifted the Cua Dai toward the beach side. The shoreline area bordering the Bien Dong (Eastern Sea) extended in 1973 to approximately 290–370 m, as compared to the shoreline in 1964 (Figure 4a).

In the 1960s (particularly in 1964), the Cua Dai estuary was about 330–340 m wide. In 1973, the Cua Dai estuary was approximately 330 m wide, but shifted toward the south. The spring accretion formed new sand bars along the Cua Dai shoreline.




(**a**) (**b**)

**Figure 3.** The historical shoreline morphological changes of the Cua Dai estuary (**a**) between 1964 and 1973; and (**b**) between 1988 and 2000 are shown in different line patterns and colors.

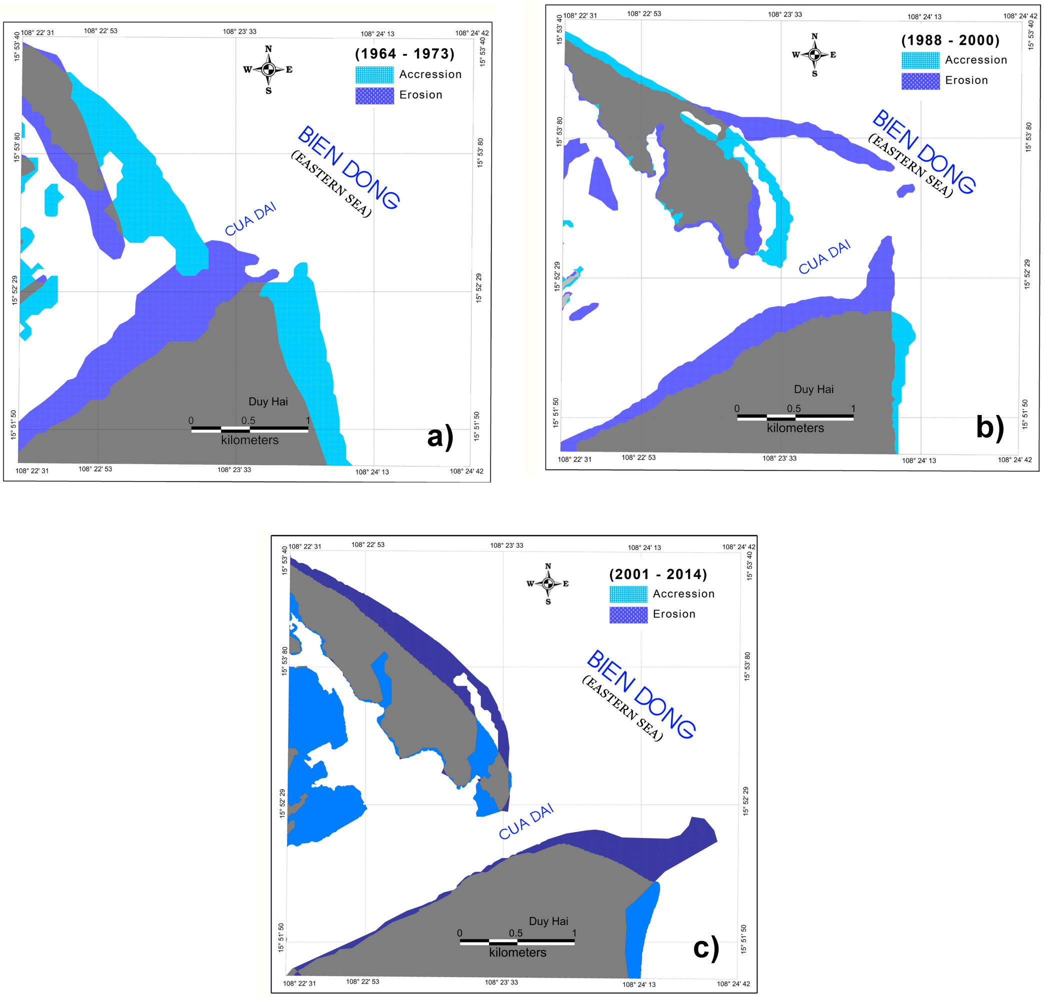



**Figure 4.** The post-class change detection during the periods of (**a**) 1964–1973; (**b**) 1988–2000; and (**c**) 2001–2014 in the Cua Dai estuary.

### 3.2. Shoreline Changes of the Cua Dai Estuary, 1981–2000

The assessment results showed that the Cua Dai shoreline had a strong fluctuation in this phase. The fluctuation of the Cua Dai estuary area tended to shift to the south between 1960 and 1980. In particular, the fluctuation significantly increased in 1988 and 1989. On the northern side of the Cua Dai, submerged sand bars came up to the water's surface, with an early moon shape approximately 1,890 m in length and 90–120 m in width, from the northern bank to the cap of the estuary. However, in January 1989, the sandbar cape was eroded or might have moved at an angle of about 30° to the eastern bank of the Cua Dai (Figure 3b). Two remaining lakes/water bodies at the northern bank of the Cua Dai estuary can be considered evidence for the movement phenomenon. In 1999 and 2000, the morphology of the Cua Dai northern shore had slight fluctuations, but the water bodies increased the area of the Cua Dai estuary.

At the southern side of the Cua Dai estuary, the movement of the sand bars was in the same direction as found between 1964 and 1980, with the erosion occurring in the northwest side and accretion occurring in the eastern side. During the period between 1988 and 1989, the movement of the sandy cape in the north of the Cua Dai estuary was also noticeable. The sand capes, which are approximately 580 m in length, were eroded and then replaced with a new sand bar of approximately 690 m in length. The sand bar became a submerged island in 1999 and disappeared in the following year (2000).

From 1988 to 2000, the sand bar established in 1988 in the north of the Cua Dai estuary had been removed, and a newly formed peninsula was found on the eastern side. There were no significant changes in estuary morphology during this period. In 1988, the early moon–like shape had eroded; and accretion occurred inside the estuary. In the southern side of the Cua Dai, the movement of the estuary showed definite erosion at the riverside (in the northwest direction) of approximately 220 to 240 m, which enlarged the estuary area by about 520 m. The accretion occurred on the eastern side of the estuary towards the Bien Dong Sea, with a length of between 90 and 110 m, and up to 210 m in some areas (Figure 4b).

### 3.3. Shoreline Changes of the Cua Dai Estuary, 2001–2014

The analysis results revealed that the shoreline experienced significant fluctuation during the 13 years of this phase. However, the Cua Dai estuary had little movement in the southern direction in comparison with the periods of 1964–1980 and 1981–2000. The movement of the shoreline on the eastern side encountered a significant fluctuation during this period. In the northern side of the estuary, the submerged early moon–like shape eroded. The erosion at the seaside tended to move into the landside, resulting in the loss of the land area in the north of the Cua Dai peninsula (Figure 5).

The erosion of the land area changed at various scales over the observed years. Between 2001 and 2002, the movement of the shoreline was approximately 50–60 m, and occurred at a lower scale than that of the period from 2002 to 2003 (roughly 80–90 m). The erosion scale was about 30–70 m during the period of 2003 to 2004. The greatest erosion period was found between 2004 and 2007, with approximately 110–130 m of the shoreline lost. The erosion of the northern side of the Cua Dai was about 50–60 m and 20–30 m during the periods of 2007–2009 and 2009–2010, respectively. In general, the shoreline of the northern Cua Dai estuary eroded roughly 230–240 m from 2001 to 2010. The erosion of the shoreline was different between years, with an average scale of around 35 m per year.

In the southern side of the Cua Dai estuary, the movements of the estuary and shoreline were different when compared with the previous periods. For instance, the greatest erosion occurred on the northeast shoreline, while accretion happened mainly on the eastern shoreline. Between 2001 and 2002, the southern side of the Cua Dai cape had about 430–480 m of land eroded. The accretion trend was similar to that of the previous phases, with accretion continuously occurring on the eastern side of the estuary, which formed a large sand bar. During the period from 2001 to 2010, this area accreted approximately 170–210 m (Figure 4c).

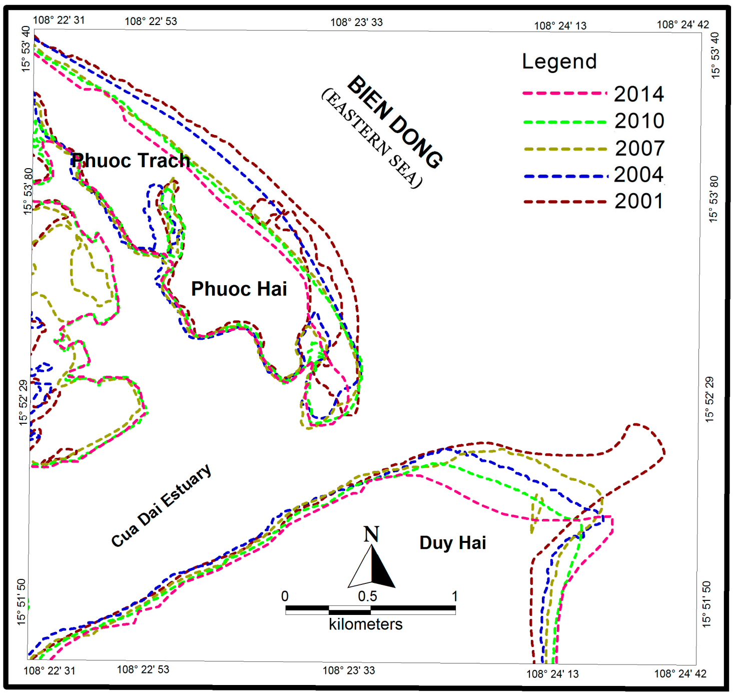



**Figure 5.** The historical shoreline morphological changes of the Cua Dai estuary between 2001 and 2014.

## 4. Discussion

The analysis of the fluctuating shoreline of the Cua Dai estuary over 50 years revealed that the submerged sandbars at the north shore were formed in 1964 and 1988. However, these submerged sandbars were either eroded or moved inward in later years. The general trend of erosion and accretion in this area showed that the Cua Dai estuary had moved in a southern direction due to erosion and accretion phenomena occurring on the northern bank of the river mouth.

Erosion and accretion are common forms of natural disasters that usually occur along the Cua Dai estuary shoreline in particular, and in the central Vietnam region as a whole. Based on the analysis of temporal shoreline changes and previous studies on the factors causing erosion and accretion of the Cua Dai estuary shoreline, we can confirm that the changing of the shoreline is caused by a combination of natural evolution processes in the estuarine areas, human impacts, and climate change. The erosion and accretion processes especially occurred as a result of three major causes: external, internal, and anthropogenic influences.

There are a number of studies showing that external causes play an important part in controlling shoreline erosion and accretion in the Quang Nam province, and particularly for the Cua Dai estuary [9–15]. The external causes comprise tropical typhoons, alongshore currents, tidal dynamics, and oceanic and riverine interaction processes. In this study, we present three major external causes that are recognized as being important for the dynamics of the Cua Dai shoreline.

### *4.1. The Effects of Tropical Typhoons on the Cua Dai Shoreline*

The wind is one of the main reasons for shoreline erosion in the Quang Nam province via the wave and current-forming processes [22,23]. The strong winds that occur from tropical typhoons remove a significant amount of coastal materials, including sand. However, the change of shoreline morphology only occurs at certain times; and lost materials are often redeposited in the area to bring the area to as it was before the typhoon. This trend is similar to that of several other areas in Central Vietnam in general [20,22,23].

Besides the effect of typhoons, the movement of water levels also affects this area. The vulnerability of the shoreline is steadily increasing, and could be considered one of the main causes of shoreline erosion. The rising sea levels due to the monsoon usually occur along the central coast in general, and particularly along the Quang Nam coast. The sea level rise during the monsoon is usually about 30–40 cm high, but often exists for an extended period, usually one week or longer. According to the historical data, around two to four tropical storms annually hit the mainland in the coastal areas of Quang Nam. Storm tracking data from 1964 to 2014 showed 35 typhoons, and tropical depressions made shoreline changes and landfall on the coast from Thua Thien Hue to Quang Nam [26]. The deadly typhoon Xangsane hit Da Nang on October 1, 2006, with strong winds at the 12–14 level in the Quang Nam province. At the Ai Nghia (Dai Loc) hydrological station (15°53′ N–108°07′ E) on the Ai Nghia River, the flood peak reached 10.77 m; and the Giao Thuy River's flood peak was 9.75 m, higher than those in 1999 and 2007. Over the course of the history of the Hoi An River, the water level once rose over 3 m, approximately 1.3 m above the third alert level (Figure 6).

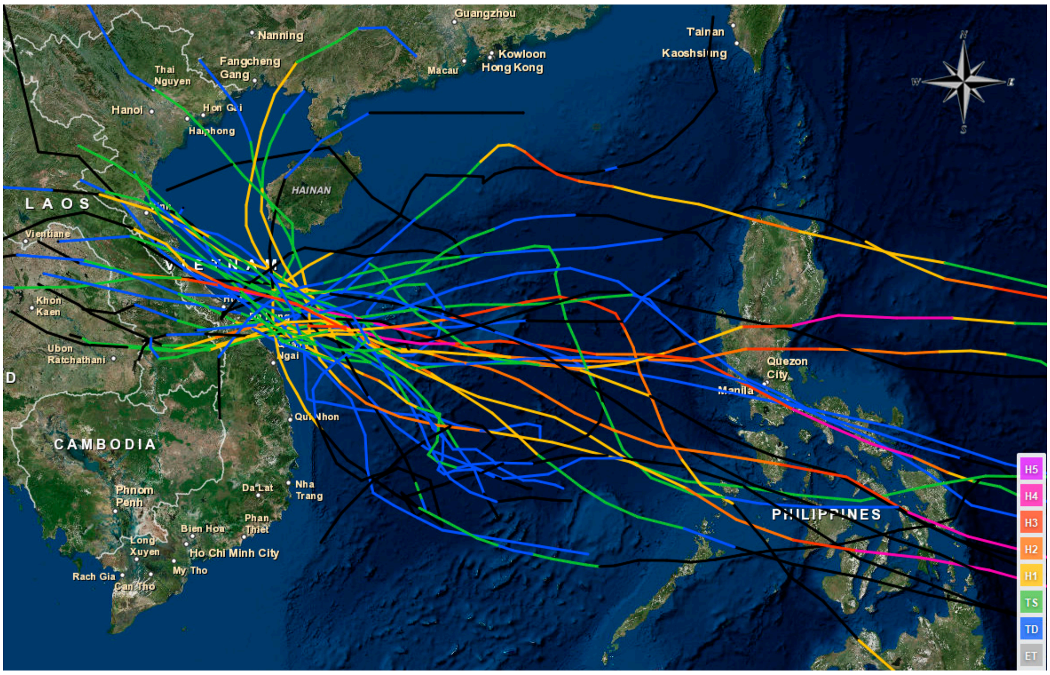



**Figure 6.** Historical typhoon tracked off the Cua Dai estuary, Central Vietnam during the period from 1964 to 2013 (Imagery source http://coast.noaa.gov/hurricanes/).

The Quang Nam coast is in the south central region stretching between latitude 12° and 16° (from Quang Nam to Khanh Hoa provinces). The rainy season usually occurs from August to November, with a focus on September, October and November. Typhoon and tropical depressions have caused major floods in this region. In addition, under the influence of recent climate change, the increase in both the frequency and intensity of typhoon and tropical depressions has been clearly recognized.

### *4.2. Effects of Seasonal Alongshore Current on Shoreline Dynamics*

Current is one of the factors that play a significant role in sediment transport. Along the Quang Nam coast, the waves meet the shoreline during the northeast monsoon from north to south, and alongshore waves from the west of the Gulf of Tonkin (southwest monsoon) are the principal factors for accretion in the area. On the east coast, the southwest monsoons occur from May to July every year. Of those, the strongest occur in June. The northeast monsoon activity starts from October to March of the next year. The monsoons are most powerful in November, December and January of the following year. The monthly distribution of wind speed is typically represented in Figure 7 for 2004. In response to the monsoon wind forcing, the currents along Central Vietnam's coasts generally move northward in the dry season, and southward in the rainy season [27].

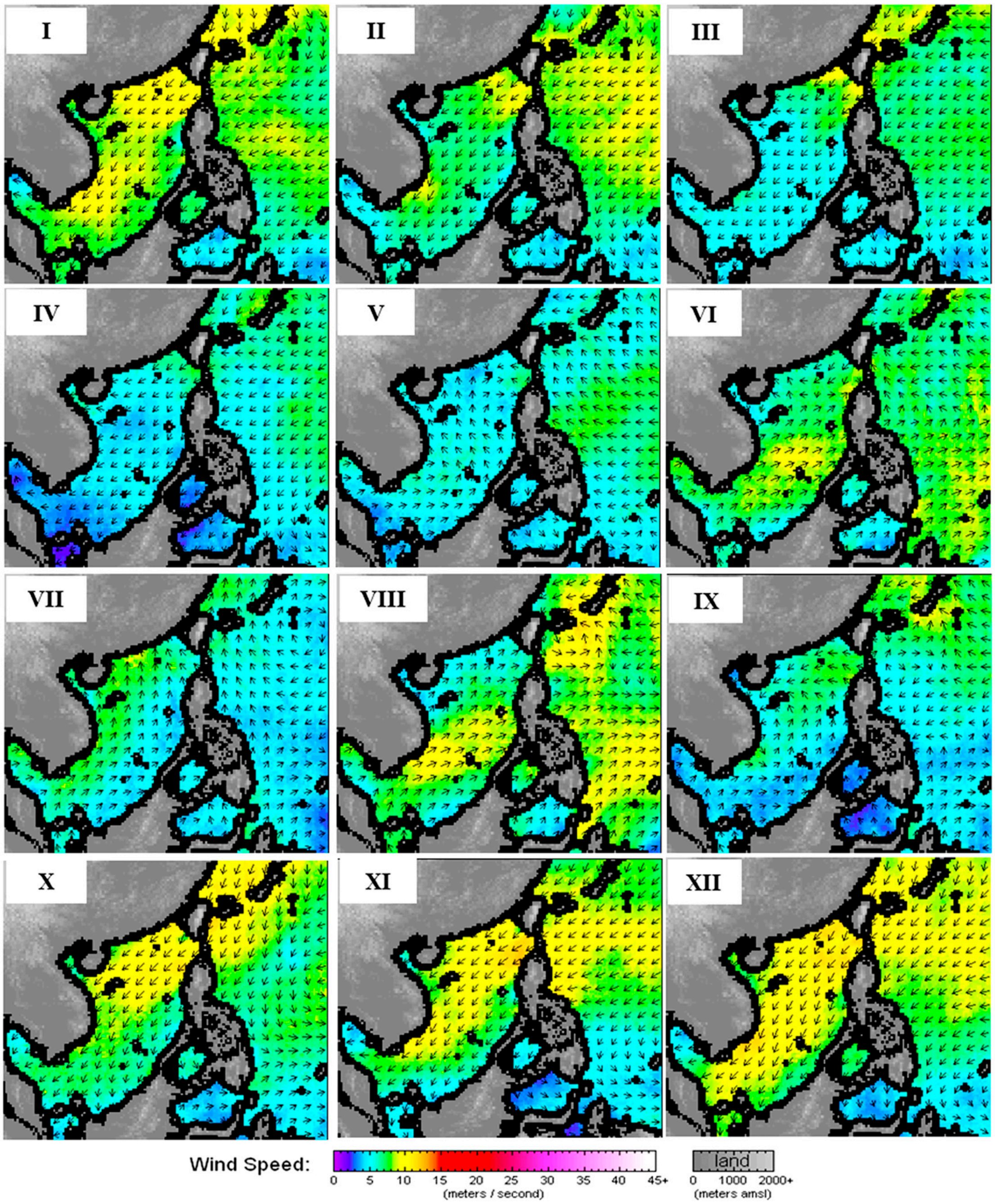



**Figure 7.** Typical average annual wind speed in 2004 of the Southeast Asian Sea, including Bien Dong, in relation to the Central Vietnam shoreline (Image source http://poet.jpl.nasa.gov).

The wind is an important factor in wave formation, causing shoreline erosion. According to Tang (2009), the wave height depends generally on the wind direction at the shore area, with large waves occurring during either the northeast monsoons or the flowing of easterly winds [28]. The annual activity of the northeast monsoon wind makes the coastal current stronger in the direction from north to south. This is considered a primary cause of shoreline erosion in the rainy season. In the dry season, the southwest monsoon is dramatically active from May to August in the reverse direction, from south to north, which causes prevailing accretion processes for the coastal areas.

When being asked to give comments on the historical shoreline trend of the region, the local residents, who have spent their entire life in the Cua Dai estuary, concluded that the *"rainy season is erosion; and "Nom" (the southeast monsoon) season is accretion"*. The local people have regarded the northeast monsoon, the north wind, and the southwest monsoon as *"Haste ("Chướng" in Vietnamese) wind"*. Therefore, the local people have believed that "*Haste wind is accretion; and north wind is erosion"*. The substantial erosion activity takes place in years with strong northeast monsoons, typhoons, and tropical depressions from the Southeast Asian Sea (including Bien Dong), which might be accompanied by flooding. Meanwhile, the accretion activity rapidly occurs in the dry season when the southwest monsoon is prevailing. The strong southwest monsoon usually has a high accretion rate. According to local residents, the accretion activity takes places at a fast rate and can builds up hundreds of meters of accreted coast within one night. When the first Cua Dai residents found these newly formed lands, they cultivated the young Australian pine tree *(Casuarina equisetifolia)* for the purpose of establishing and unofficially owning the new accretion areas. However, these areas are in a sensitive condition, and also vulnerable to erosion during the next rainy season.

### *4.3. Effects of Wave and Tidal Dynamics on Shoreline Changes*

Wave and tidal dynamics are also factors that damage the coastal works and cause shore erosion. In addition to the direct impact of wave pressures, the energy from wave currents causes seabed and shore sediment transport and erosion. Along the central coast region, the Quang Nam province is home to the largest wave energy, especially in two critical areas: the Cua Dai estuary and the Cua Lo inlet in the An Hoa lagoon.

Gravitational forces of the moon and Sun on the Earth's surface form the tides, which act in accordance with their cycles. The tidal system on the Quang Nam coast is affected by the tidal system of the Southeast Asian Sea, with the spring and ebb tide occurring twice a day (ranging from 0.5 to 1.0 m). The tidal regime of the study area was assessed through water level data at the closest tide gauge station in Da Nang (16.11° N–108.21° E), which gives the coastal tides of the Cua Dai estuary. The combination of tropical typhoons, high tide, and sea level rising create enormous waves, with a large amount of energy causing destruction and erosion.

In addition to external reasons, the erosion of the Cua Dai shoreline is also affected by numerous internal and external (anthropogenic) reasons. The internal reasons include the impact of newly forming activities and tectonic movements that cause sliding shoreline morphology, which result in the erosion and accretion of the shore. According to previous studies conducted in this area by Son (2002), Mau (2006), and Binh (2007) [9,20,21], over a 60-year period (1965), a submerged sandbar, at a depth of approximately 2 m in the north of the Cua Dai estuary, extended southward. This sandbar has also been shown on a US Navy map published in 1964. However, in 1973, Landsat 1 satellite image showed that the submerged sandbar had disappeared on the northern side of the Cua Dai estuary. In addition, unsustainable socioeconomic development activities have also affected the Cua Dai estuary shoreline. For instance, land reclamation, irrigation, mining, exploitation of construction materials, and mangrove deforestation can cause erosion and accretion of the shore. The consequence is often presented at the local level on a relatively small scale. Furthermore, there are some subjective reasons, including the construction of dams upstream of the Thu Bon river system, that change the water flow downstream, and affect the flow and sedimentation processes.

In general, the dynamic trend of shoreline changes in the Cua Dai estuary follows the dynamic model of the ebb tidal delta morphology in the interaction between waves and tidal currents [29]. Examining the Cua Dai estuary morphology over a period of 50 years shows that its morphology represents the alongshore current dominant model. Thus, based on the FitzGerald et al. (2010) model, the morphology change and sediment transport in the Cua Dai estuary during the last 50 years also belongs to the phenotypes delta ebb tidal detail [30]. There is a dominance of alongshore current and sand dunes, as well as the early formation of sandbars and a shift to the shore side at different phases. Thus, the field data on the accretion and erosion phenomena of the coastal area are meaningful in the retrieval of data derived from multi-temporal remote sensing images. However, the field data collection is always time-consuming and costly when performed over a large geographic area. Therefore, it is recommended that future research on applying remote sensing data for the assessment of shoreline variations needs to focus on filed data collection as much as possible in order to enhance the adjustment capacity and the accuracy of interpretation results from satellite remote sensing images.

## 5. Conclusions

In this paper, we presented the shoreline dynamics of the Cua Dai estuary over a period of 50 years (1964–2014) by using geographic information systems techniques, multi-temporal satellite remote sensing images (ALOS-AVNIR2 and Landsat imageries), and field survey data. The assessment of shoreline changes was divided into three phases, namely 1964–1980, 1981–2000, and 2001–2014. Our analysis results revealed that over the last 50 years, the shoreline changes have dramatically occurred in the period between 1964 and 1980. The general trend of the erosion and accretion at the Cua Dai estuary showed that the river mouth moved towards the south due to the erosion of shorelines in the north and river bank in the south of the Cua Dai estuary. Additionally, possible factors influencing the shoreline changes include tropical typhoons, alongshore currents, and wave and tidal dynamics.

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**Author Contributions:** There four co-authors contributed equally to this article. Hoang Cong Tin, Nguyen Quang Tuan and Luong Quang Doc conceived, designed and performed the field work and experiments; Hoang Cong Tin and Nguyen Quang Tuan analyzed the data and wrote the manuscript; Luong Quang Doc and Tran Anh Tuan have provided substantial edits and reviews on the many early drafts of this manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

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