JOURNAL OF
HYDRO-METEOROLOGY

Research Article

Morphological changes at Nhat Le estuary under hydro-meteorological influence

Vu Dinh Cuong[1]*, Nguyen Thanh Hung[1], Tran Dinh Hoa[2]

[1] Key Laboratory of River and Coastal Engineering (KLORCE); cuongvd.vkhtlvn@gmail.com; nthung@vawr.org.vn
[2] Vietnam Academy for Water Resources (VAWR); tranhoa08@gmail.com

*Corresponding author: cuongvd.vkhtlvn@gmail.com; Tel.: +84–396806099

Received: 15 January 2025; Accepted: 14 March 2025; Published: 8 June 2025

Abstract: Nhat Le estuary is located on the Central coast of Viet Nam, where it always has strong morphological changes under the influence of seasonal changing dynamic factors. Based on the analysis of shoreline and topography data, the article presents some assessments on the relationship between hydro-meteorological conditions and changes in the morphology of the Nhat Le estuary. The assessment results show that: (1) The seasonal variation of wave and river discharge factors have a strong impact on morphological changes in the Nhat Le estuary. Width of river mouth and "arrow-shaped" sandspit on the southern bank of the estuary are affected by the river discharge factor, while the main channel and sandbar of the estuary are strongly affected by the wave factor; and (2) This has led to the creation of a general diagram depicting the morphological change cycle of the Nhat Le estuary under the influence of wave and river flow factors. The research results will contribute to further clarifying the causes and trends in the morphological development and providing crucial information for proposing solutions to stabilize the Nhat Le estuary.

Keywords: Morphology; Nhat Le estuary; Morphological change; Morphology of estuaries.

1. Introduction

Estuaries are the transitional zone between the sea and inland rivers, where marine dynamic factors and river dynamic factors interact and influence hydrodynamic processes. The estuaries in the Central coast of Viet Nam have great morphological changes with the influence of tidal, wave and river flow processes [1]. Due to the characteristics of rivers in the Central coast, where marine dynamic factors play a major role with long-lasting effects, they have determined the morphological characteristics of estuaries, which are eroded during the flood season and sedimented, narrowing the river mouth during the dry season [2–3].

Nhat Le estuary is located on the Central coast, in Dong Hoi city, Quang Binh province, with geographical coordinates approximately 17°29' North latitude and 106°38' East longitude. Different from other estuaries in this area, the section of Nhat Le estuary before pouring into the East Sea (from Quan Hau to Dong Hoi city) has a South-North flow direction and changes to East-North direction when it flows into the East Sea, the coastline of the estuary area has a Northwest - Southeast direction (Figure 1). The hydrodynamic regime in the Nhat Le coastal estuary area is quite complicated because of the interaction between the river and the sea flow and it has a seasonal variable hydrodynamic regime [1, 4]. To maintain the waterway transport channel and socio-economic development in the Nhat Le estuarine area, they dredged the channel and built beach restoration works. The seawall on the coast of

My Canh (at SunSpa resort), south of Nhat Le estuary; it was built on the sand dune in the early 2000s and expanded to shoreline/beach face in 2009. Main channel of Nhat Le estuary was dredged in 2020, and a temporary construction has been built to create a dredged material disposal site by geotube work in front of the SunSpa resort seawall (Figure 1). Based on the actual changes in the Nhat Le estuary in recent years, it can be preliminarily concluded that these structures have had a significant impact on the morphological changes of the estuary.

Figure 1. Map of study area.

Although there has been some research about Nhat Le river estuary [5–12], but mainly focuses on analysis and evaluation of hydrodynamics, sand transport, shoreline change, erosion and accretion; they have not studied, analyzed and evaluated the morphological changes of Nhat Le estuary under the influence of hydro-meteorological conditions. The relationship between the above factors has been clarified in this study through the synthesis and analysis of hydrological data (focusing on two factors: river discharge, wave), and shoreline, channel topographic data. Due to the phased impact of the structures built at the Nhat Le estuary on the morphological changes, as previously mentioned, this study divides the analysis into two main periods: (1) the period from 1999 to 2009, and (2) the period from 2009 to 2019. Additionally, a preliminary assessment of shoreline changes in recent years, from 2020 to 2024, is also included. The research results will contribute to further clarifying the causes and trends in the morphological development and providing crucial information for proposing solutions to stabilize the Nhat Le estuary, coastal management, engineering, or climate change adaptation.

2. Materials and Methods

2.1. Data collection

The data used for the research in this paper include hydro-meteorological data, remote sensing images, and topographic maps over a 25-year period (from 1999 to 2024); with each data type having a different time span depending on the source of the original data collected. The data were processed to ensure synchronization of time and space with the same altitude system and coordinates according to the national system.

- Hydro-meteorological data, including data on water level, discharge at the estuary and offshore wave, in which: Water level data at Dong Hoi hydrological station (2012-2024), located about 1.5 km from the estuary (Figure 1); offshore wave (1999-2024) data from NOAA's Wave watch 3 global wave model [13], wave data in the Nhat Le estuary (2018) inherited from the research results [1]; and Nhat Le estuary discharge (1999-2024) calculated from the hydrological - hydraulic model of the Nhat Le river basin, the model is inherited and updated and further developed from the research results of the project KC08.16/16-20 [5]. This hydrological - hydraulic model has been calibrated and validated to ensure the required reliability.

- Remote sensing image data: including 02 types of optical images, in which Landsat images with a resolution of 30 m in the period (1999-2024) to interpret the location of the shoreline; Sentinel-2 images with a resolution of 10 m in the period (2015-2024) to explain the location of the shoreline and bottom topographic depth in the Nhat Le estuary.

- Topographic data: topographic maps with 1:5,000 scale in the area of Nhat Le estuary (Figure 2) collected from surveys of projects in the period from 2005 to 2019 [5, 8–10].

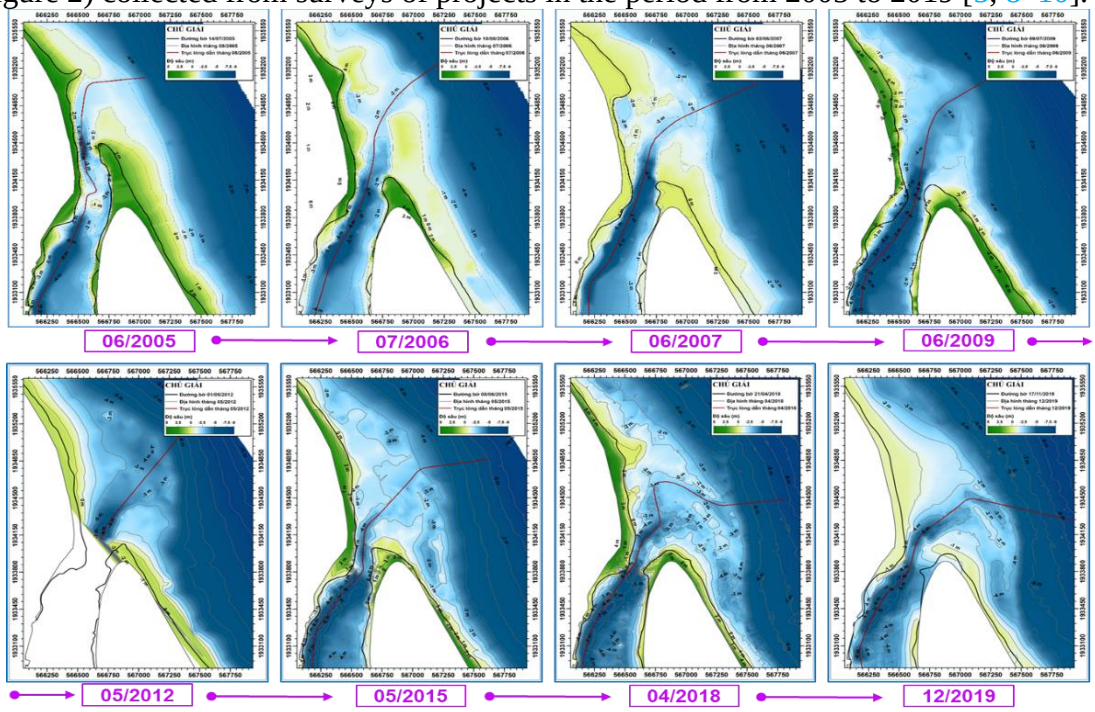

Figure 2. Topographic measurement data in the Nhat Le estuary from 2005 to 2019.

2.2. Shoreline detection using optical remote sensing

The remote sensing image analysis method to interpret the location of the shoreline has been mentioned in many previous studies as [5, 7, 14–22]. Several spectral indices, including Normalized Difference Water Index (NDWI), Modified Normalized Difference Water Index (MNDWI), Automated Water Extraction Index (AWEI), and Water Index (WI), were used for shoreline detection.

In this study, the NDWI (Normal Difference Water Index) was used to determine the location of the shoreline. The shoretline is determined through the remote sensing image process: Collecting Landsat and Sentinel-2 image data; Enhanced remote sensing image quality; remote sensing image correction; NDWI index calculation; Threshold fractionation, shoreline extraction based on NDWI index [14].

2.3. Estimation of bathymetry by empirical regression method

Figure 3 is a summary diagram of the process for interpreting shallow water bathymetry from Sentinel-2 satellite images. The paper uses bathymetry data of the topographic survey at Nhat Le estuary in April 2018 (Figure 3a) and a Sentinel-2 image taken on April 21, 2018, to develop a correlation equation for interpreting bathymetry from Sentinel-2 images.

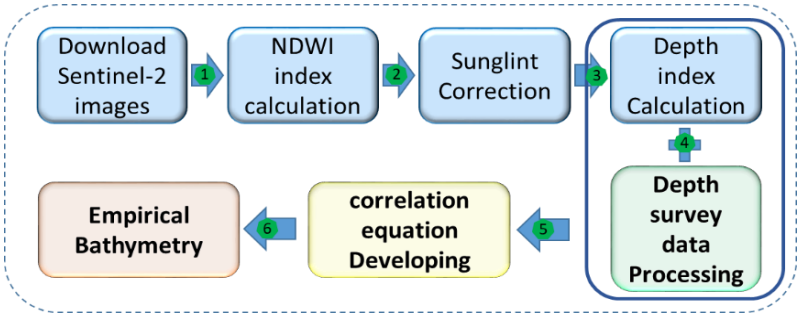

Figure 3. Coastal seabed terrain depth interpretation from Sentinel-2 image.

(3) Sunglint Correction:

Use the correction method of [17] describes the linear relationship between NIR and observable channels based on the regression equation of image pixels.

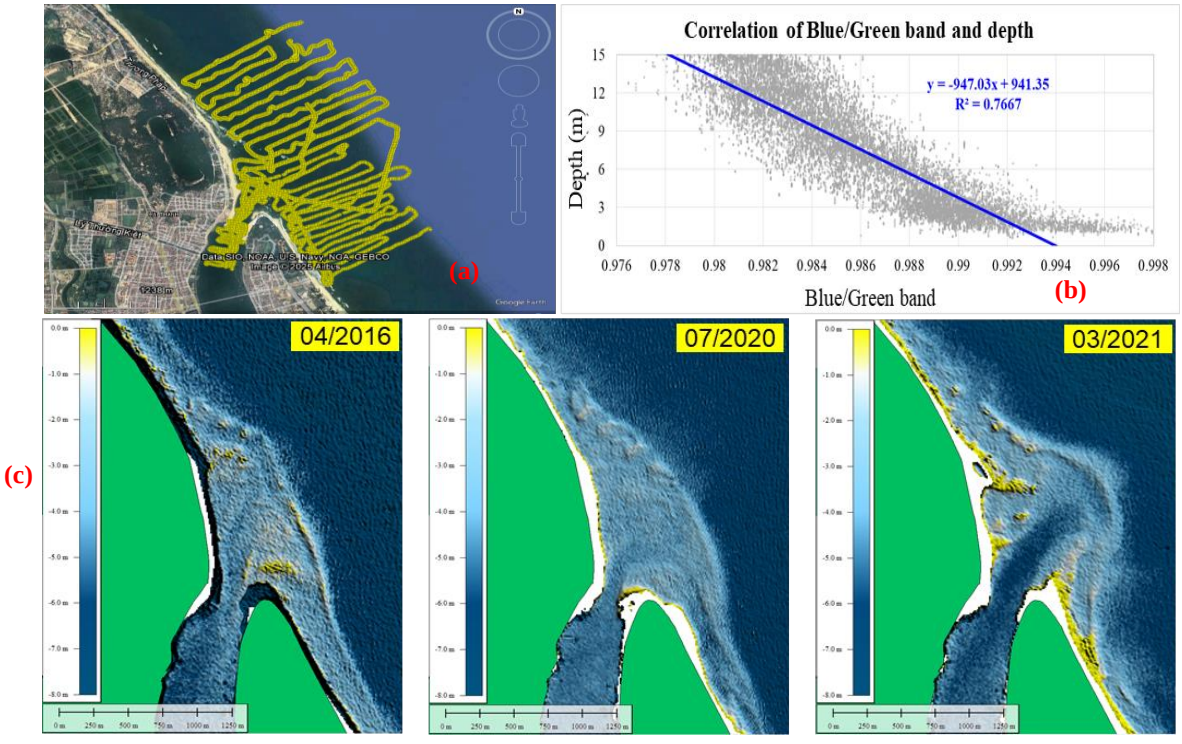

Figure 3. Correlation and depth resolution results from Sentinel-2 images: (a) Location of bathymetric points for correlation; (b) Correlation of Blue/Green band and depth; (c) Results of depth analysis at some time in the Sentinel-2 image.

(4) Calculation of the depth index:

The study uses the formula developed by Stumpf [18] based on the principle that each spectral channel will have a different level of absorption for water. This score changes when the actual depth changes.

(5) Develop a correlation equation between the depth index and the measurement data:

Based on the depth index for the scene on April 21, 2018 with the actual depth data measured in April 2018, the correlation equation in the form of a linear function y = -947.03x + 941.35 (where y is the corresponding depth of interpretation at the Sentinel-2 pixel with the Blue/Green band ratio value), with a good correlation coefficient with a value of R^2 = 0.767 (Figure 3b). Using this correlation equation to interpret the bathymetry from Sentinel-2 images captured at different times from 2015 to 2024, some of the bathymetry analysis results are shown in Figure 3c. The results of this interpretation demonstrate the potential application of Sentinel-2 optical remote sensing images for interpreting the shallow water bathymetry. However, the drawback of optical remote sensing images is that they are affected by clouds and weather conditions, which can lead to errors in accurately determining the bathymetry [23–25].

3. Result and Discussion

3.1. Seasonal fluctuations of hydro-meteorological conditions in the Nhat Le estuary

In the Nhat Le estuary, the Northeast monsoon season from October to March of the next year, there are large waves, and in which from October to December coincides with the flood season in the river; on the contrary, the Southwest monsoon season, there are small waves that coincide with the dry flow season in the river from May to August and the seasonal transition months are April and September [1]. Figure 5a shows the correlation between the average monthly characteristics of wave height and estuary flow in the period 1999-2023. The wave factor and river flow both have distinct seasonality. The flow from the river basin to Nhat Le estuary is the largest in the flood season months (from October to December) with an average monthly flow of 100-400 m^3/s; Meanwhile, in the remaining months of the year, the flow rate is very small, on average only less than 50 m^3/s. In the flood season months, the flow in large rivers also coincides with offshore with the largest waves of the year; from the first to the ninth month, the large wave conditions are still maintained due to the activity of the Northeast monsoon with an average wave height of about 0.75-1.75 m, but in the river the flow is the smallest in the year; from May to August is the period with conditions of offshore waves and small river flow. To better understand the seasonal variation of these 2 factors, consider the variation of the offshore wave factor and the river flow in an hourly series of data for a representative year (2018) (Figure 5b). The river flow is small in the period of January to September, so it mainly fluctuates according to the tidal cycle. From October to December, there are some flood events, so the river flow has a sudden increase. Offshore waves in the Northeast monsoon season and river flood season have a large wave height of about 0.5-4 m, in summer, the height of small waves is only about 0.25-1.75 m.

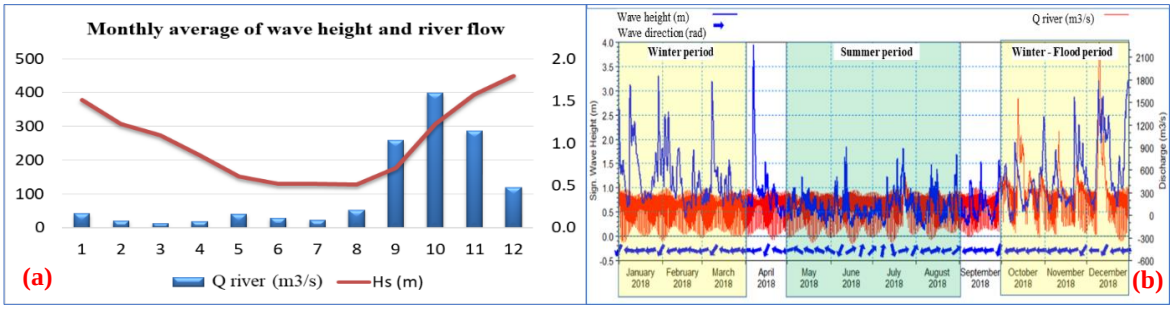

Figure 5. Correlation of seasonal fluctuations of hydro-meteorological characteristics of Nhat Le estuary: (a) Monthly average of wave height and river flow in the period 1999-2023; (b) Correlation of seasonal fluctuations of wave height and river flow.

Details for the Nhat Le estuary, the results of the research and evaluation [1] on the analysis of seasonal fluctuations in the Northeast and Southwest winds of wave characteristics in 1 representative year (2018) in Nhat Le estuary shows:

During the Northeast monsoon: In the coastal area north of Nhat Le estuary, the main wave direction is the Delta accounting for 53% and the Delta accounting for 38%, with the largest wave height reaching 2 m. In the southern coastal area, the main direction of the wave is the Delta accounting for 56% and the Delta accounting for 35%, with the wave height in the range of 0.1-2 m. The estuary has large waves, the wave height can reach 2 m with the direction of the Delta and Delta waves dominating the mainstream, respectively at the rate of 57% and 33% (Table 1).

During the southwest monsoon: The waves are much smaller than in the Northeast. In the northern coastal area, the waves with the main direction are the Delta to the East, accounting for 43% and 36%, respectively, with small wave heights of 0.1-0.8 m. In the southern coastal area, the waves from the Delta to the East accounted for 46% and 33%, respectively, with a small wave height of about 0.1-0.8 m. The wave estuary area with the main direction is the East and the delta, accounting for 58% and 24%, respectively, with a wave height of 0.1-1 m (Table 1).

Table 1. Seasonal fluctuations in the year in the Nhat Le estuary.

Location of wave points	Northeast monsoon season						Southwest monsoon season					
	Wave Direction		Wave Direction		Wave Direction		Wave Direction		Wave Direction		Wave Direction	
	Hs (m)	Per. %	Hs (m)	Per. %	Hs (m)	Per. %	Hs (m)	Per. %	Hs (m)	Per. %	Hs (m)	Per. %
North Coast	0.1-0.7	4.5	0.1-2.0	38	0.1-2.0	53	0.3-1.2	6	0.2-0.8	43	0.1-0.4	36
River mouth	0.1-0.7	4.1	0.1-2.0	33	0.1-1.9	57	0.3-1.3	8	0.2-1.0	24	0.1-0.8	58
South Coast	0.1-0.7	3.6	0.1-2.0	35	0.1-2.0	56	0.3-1.2	6	0.2-0.8	46	0.1-0.4	33

The estuary has the strongest dynamic regime in the Northeast monsoon and the flood season in the river, the weakest in the southwest monsoon and dry season in the river. Due to the impact of this dynamic regime, the morphology of the estuary also undergoes seasonal variations. The analysis and evaluation of the morphological change trends of the estuary over the periods will be presented in the following section.

3.2. Shoreline changes in the Nhat Le estuary

Based on the hydro-meteorological characteristics with quite obvious seasonality as analyzed, the study selected Landsat and Sentinel-2 imagery scenes to interpret the shoreline position according to 2 seasons respectively, each season of the year is represented by a predicted shoreline location; the scenes in the period of January to April and September to December represent the winter coastline (Northeast monsoon, flood season); the scenes from May to August represent the summer coastline (Southwest monsoon, dry season). From the data analyzing the location of the shoreline, the range of shoreline fluctuations in the Nhat Le estuary can be summarized according to two seasons of the year and in each period (Figure 6). From 1999 to 2009, in winter and summer, there were dunes on the north bank, the south with a nose towards the estuary, in which the sandspit on the southern bank of the estuary were strongly developed extending across the estuary in the form of a "arrow-shaped sandspit" parallel to the coastline; the width of the estuary tends to narrow and extend towards the North bank (Figure 6a). From 2009 to 2019, the northern bank only had small dunes in summer, the length of the southern dunes was significantly shortened, the angle of the dunes tended to rotate towards the sea and the width of the estuary tended to be wider than in the previous period (Figure 6b). In the years from 2020 to 2024, there will no longer exist the Northern sandspit, the Southern sandspit will no longer protrude towards the sea but will be narrowed and moved into the estuary (Figure 6c).

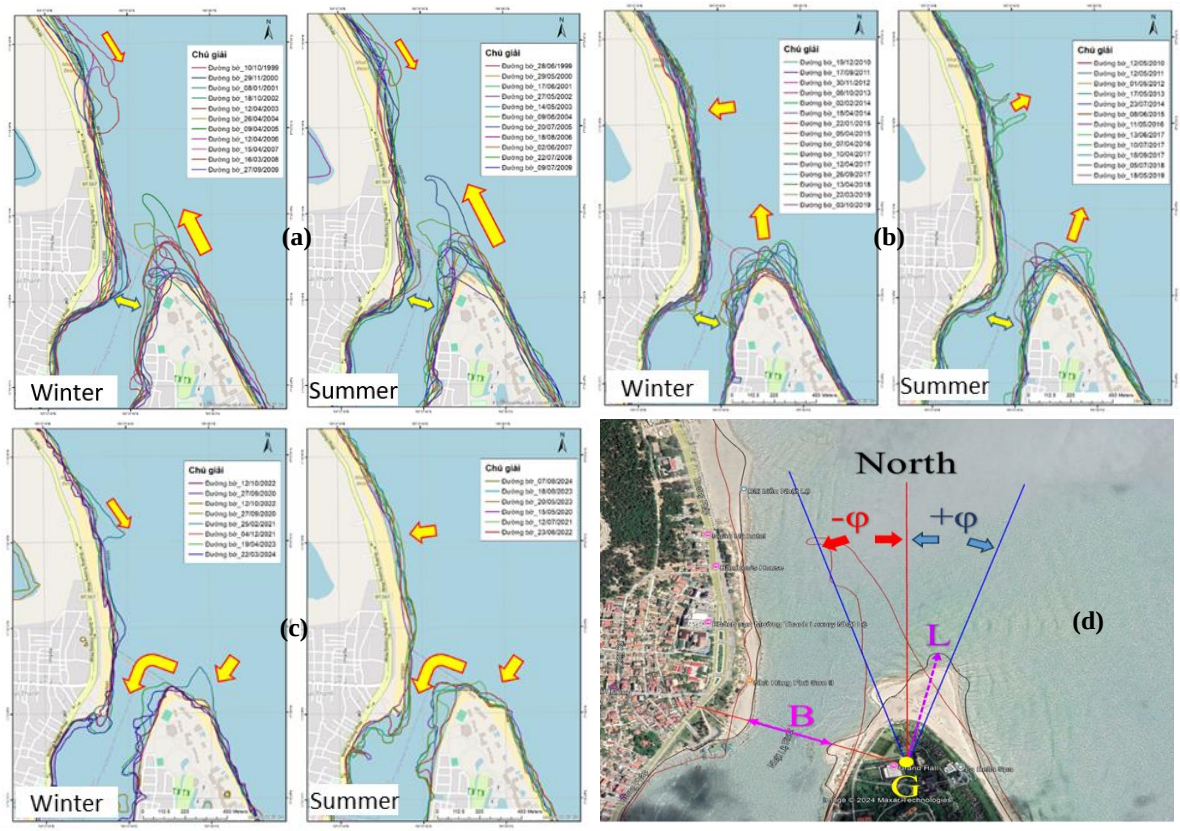

Figure 4. Seasonal shoreline changes over the periods: (a) The period 1999-2009; (b) The period 2009-2019; (c) From 2020 to 2024; (d) Characteristics of the arrow-shaped sandspit.

To quantify the fluctuation trend of the estuary shoreline and the arrow-shaped sandspit over the periods, the study statistically calculated some characteristics of the maximum river flow (Q_{max}), the average width of the river mouth (B), the angle relative to the North (φ) and the length (L) of the arrow-shaped sandspit from the reference origin (G). The convention on the characteristics of the arrow-shaped sandspit is illustrated as in Figure 6d; the statistical values of the features as in Table 2. The analysis statistics show that the general trend of changes in the characteristics of the period after 2009-2019 compared to the period before 1999-2009 is as follows: river flow (Q_{max}) tends to increase, increasing from 722 m^3/s to 928 m^3/s on average; the average width of the estuary (B) tends to decrease, the average decreases from 199 m to 120 m; the rotation angle (φ) of the arrow-shaped sandspit in both winter and summer tends to increase, meaning the arrow-shaped sandspit gradually rotates towards the sea; the length (L) of the arrow-shaped sandspit in both Winter and Summer tends to decrease, decreasing from 269 m to 160 m on average.

Table 2. Fluctuations of river flow and characteristics of the width of the river mouth, length and angle of the arrow-shaped sandspit over the years.

Year	Qmax (m^3/s)	B(m)	Angle φ (degrees)		Length L (m)		Year	Q_{max} (m^3/s)	B(m)	Angle φ (degrees)		Length L (m)	
			Winter	Summer	Winter	Summer				Winter	Summer	Winter	Summer
1999	3028	199	-12	-8	242	268	2010	3723	231	-30	-23	106	239
2000	1027	222	-15	0	64	201	2011	2992	255	-12	0	78	105
2001	1549	220	-43	-11	98	74	2012	1373	209	-26	-5	40	176
2002	1516	240	-25	-46	80	102	2013	2392	223	10	-31	60	108
2003	722	207	-15	-19	241	264	2014	928	134	-10	-21	178	141
2004	1274	250	-27	-31	299	403	2015	1899	151	-32	-39	241	210
2005	2502	293	-15	-17	526	620	2016	3464	194	-21	-30	143	193

Year	Qmax (m^3/s)	B(m)	Angle φ (degrees)		Length L (m)		Year	Q_{max} (m^3/s)	B(m)	Angle φ (degrees)		Length L (m)	
			Winter	Summer	Winter	Summer				Winter	Summer	Winter	Summer
2006	2248	336	-16	-13	243	289	2017	959	214	15	21	258	243
2007	2434	307	-15	-14	288	247	2018	968	120	-18	-37	129	83
2008	2660	274	-18	-28	250	260	2019	2752	166	-35	-12	86	98
2009	2388	260	-10	-22	64	227							
Ave.	1941	255	-19	-19	218	269	Ave.	2145	190	-16	-18	132	160
Min	722	199	-43	-46	64	74	Min	928	120	-35	-39	40	83
Max	3028	336	-10	0	526	620	Max	3723	255	15	21	258	243

3.3. Synthesis and analysis of morphological changes in the Nhat Le estuary

From the source of topographic map data, surveying and topographic interpretation from Sentinel-2 images, a dataset showing topographic trends including elements of shorelines, main channel and sandbar was synthesized to study and evaluate the morphological changes through periods.

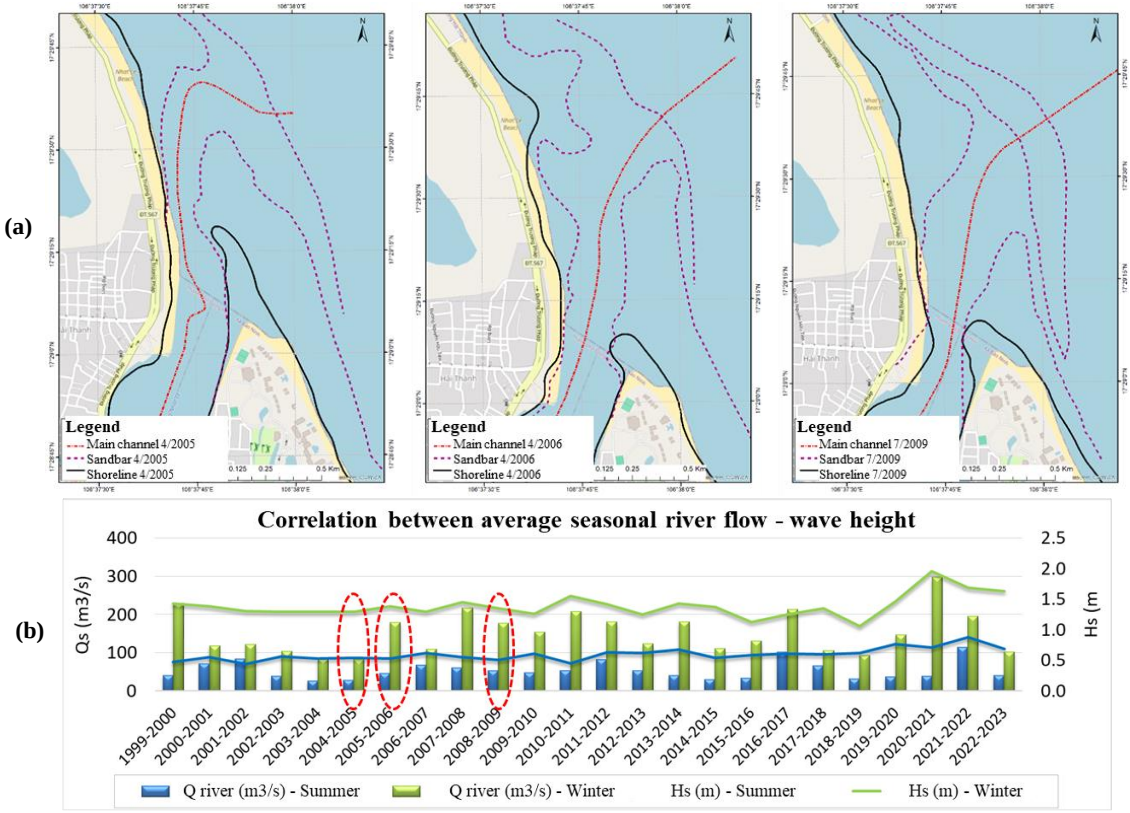

Figure 5. Correlation between river flow, waves and the morphology of Nhat Le estuary in the period 1999-2009: (a) Morphology of Nhat Le estuary in the period of 2005 - 2006 - 2009; (b) Average seasonal river flow and wave in the year, period 1999-2023.

Figure 7a shows the form of the Nhat Le estuary at some times in 2005, 2006, 2009 representing the period 1999-2009 and Figure 7b shows the typical values of river flow and seasonal average waves of each year in the period 1999-2023. When simultaneously examining the estuary morphology corresponding to the average values of river flow and waves at a given time, it is possible to see the connection between these processes. In 2005, when the river flow and waves were small (they were also small from 2002 to 2004), the river estuary form with the arrow-shaped sandspit on the south bank developed extending across the estuary, the main channel was pressed tightly and shifted very far towards the north bank, the sandbar on the south bank extended in the direction of the arrow-shaped sandspit and was pushed towards the near shore. In 2006, the river flow and waves were larger, so the estuary took the form with the sandspit on the south bank being

shortened, the estuary was widened with the main channel moving towards the middle of the river mouth, and the sandbar on the south bank was stretched and pushed towards the sea. There was a large river flow and waves in 208 and 2009 so the estuary was expanded, the sandbar in the South, North and in front of the estuary were all expanded towards the sea.

Similarly, the shape of Nhat Le estuary is considered simultaneously with the average values of river flow and wave at a certain time in the period 2009-2019 (Figure 8). In 2012, there was a large river flow and waves, the estuary had a form with a short sandspit on the south bank, a relatively wide estuary, a relatively straight main channel near the middle of the river mouth, and the sandbar on the north bank and the south bank were developed to the sea. In 2015, the river flow was small and the waves were large, so the estuary was narrowed a lot, the southern arrow-shaped sandspit expanded and forced the main channel towards the North bank, the sandbar was narrow and scattered into alternating sedimentation and erosion areas. In 2017, there was a large river flow and waves, so the estuary was expanded again, the main channel was in the middle of the river mouth, the sandspit on the south bank was short and facing the sea, the sandbar expanded towards the sea and there were alternating sedimentation and erosion areas.

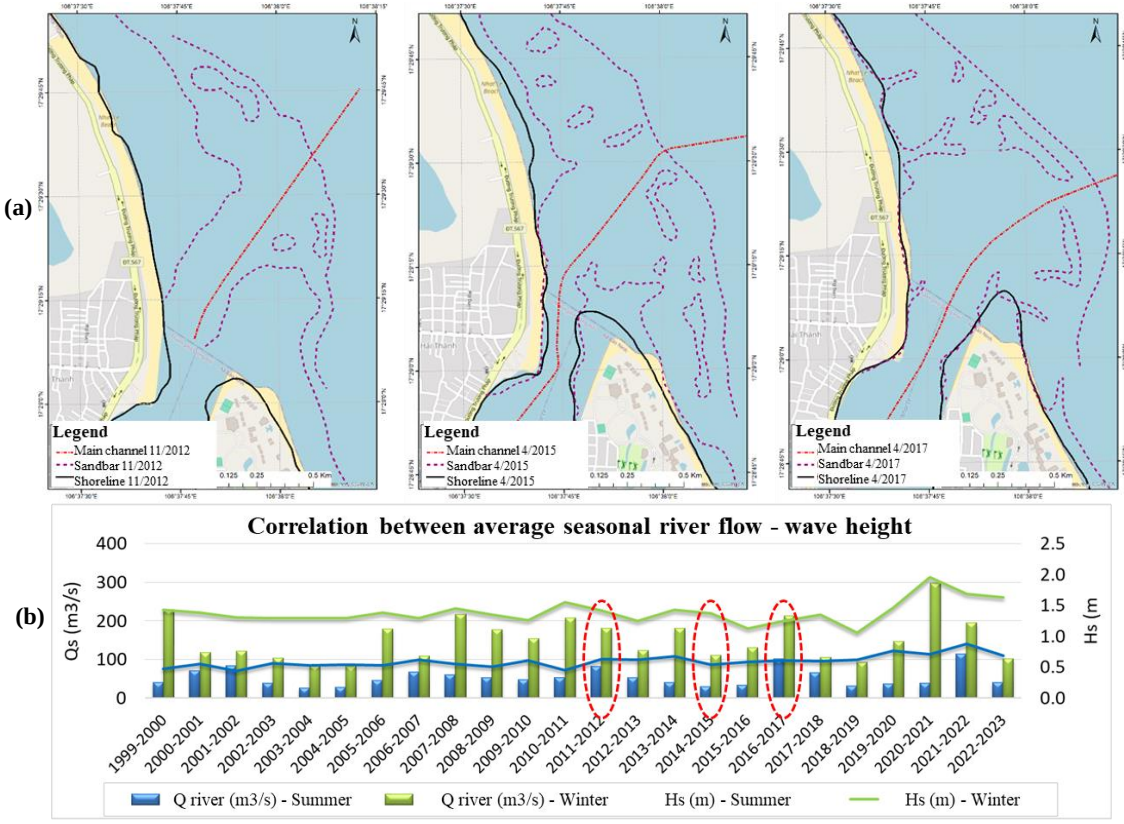

Figure 6. Correlation between river flow, waves and the shape of Nhat Le estuary in the period 2009-2019: (a) Morphology of Nhat Le estuary in 2012, 2015 and 2017; (b) Average seasonal river flow and wave in the year (1999-2023).

3.4. Morphological changes of Nhat Le estuary under the influence of hydro-meteorological conditions

Based on analyzing the fluctuations of river flow and wave factors and morphological changes (including elements of shoreline, main channel, sandspit, sandbar) in 2 periods: 1999-2009 and 2009-2019, the study has generalized into a diagram describing the cycles of morphological changes of Nhat Le estuary under the influence of hydro-meteorological conditions such as Figure

9. In the cycles of morphological changes of Nhat Le estuary, there will be 3 basic typical forms of the periods: (1) Wave dominated stage, (2) River flow - wave dominated stage, (3) River flow dominated stage. The cycles for the period 1999-2009 (Figure 9a) and for the period 2009-2019 (Figure 9b) similar; however, the morphology in the later period has a shorter sandspit on the south bank with the direction of rotation towards the sea, the main channel moved towards the middle of the river mouth, the sandbar on the north and the south bank narrows and is scattered into more alternating sedimentation and erosion areas than in the previous period.

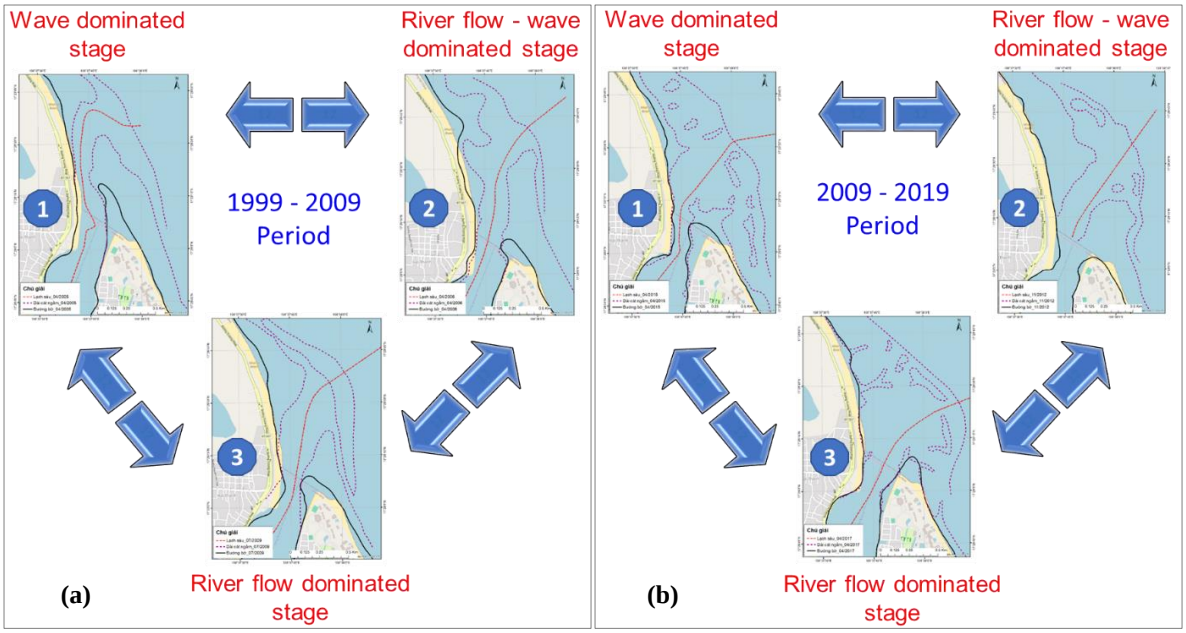

Figure 7. The cycles of morphological changes of Nhat Le estuary through the periods: (a) Morphological changes in the period 1999-2009; (b) Morphological changes in the period of 2009-2019.

4. Conclusion

The study analyzed and assessed the morphological changes of the Nhat Le estuary under the influence of hydro-meteorological conditions based on the combination of remote sensing image, bathymetry, and hydrological data, with a multi-year data series focused on the period from 1999 to 2019. The main finding results achieved: (1) Through the analysis of the monthly average characteristics of wave height and river discharge in the period 1999-2023, there is a clear seasonality of hydro-meteorological conditions in the Nhat Le estuary; (2) There has been a significant seasonal changes in the shoreline positions between winter and summer, and notable differences have occurred in two periods of 1999-2009 and 2009-2019. A detailed assessment of the shoreline and sandspit changes on the southern bank of the river mouth shows the trends: the average width of the river mouth tends to decrease, the angle of rotation of the sandspit tends to increase, meaning the sandspit is gradually rotating towards the sea; and the length of the sandspit tends to decrease; (3) It can be generalized into diagrams describing the cycles of morphological changes of Nhat Le estuary under the influence of wave and river discharge factors. The cycles include three basic typical forms of the periods: Wave dominated stage; River flow - wave dominated stage; and River flow dominated stage.

In conclusion, the research results would contribute to further clarifying the causes of fluctuations and trends in the morphological development of the estuary, providing crucial information for proposing solutions to stabilize the Nhat Le estuary. Future work may expand this

research to other estuaries in the Central coast of Viet Nam where similar fluctuations occur or study on modeling the changes in shoreline, morphology of estuaries, and coastal erosion patterns that may arise from storm impacts; or human-induced changes to other characteristics of estuaries.

Author Contribution: Constructing research idea, selecting research method: Vu Dinh Cuong, Nguyen Thanh Hung. Writing original draft preparation, and review, editing: Vu Dinh Cuong, Nguyen Thanh Hung, Tran Dinh Hoa.

Conflicts of Interest: The authors declare that this article was the work of the authors, has not been published elsewhere, has not been copied from previous research; there was no conflict of interest within the authors.

References

1. Cham, D.D.; Son, N.T.; Minh, N.Q.; Hung, N.T.; Thanh, N.T. Hydrodynamic condition modeling along the North-Central Coast of Vietnam. *Eng. Technol. Appl. Sci. Res.* **2020**, *10(3)*, 5648–5654. https://doi.org/10.48084/etasr.3506.
2. Tung, T.T. Morphodynamics of seasonally closed coastal inlets at the central coast of Vietnam. PhD, Delft University of Technology, the Netherlands, 2011.
3. Tien, L.N. Hydrodynamics and morphodynamics of a seasonally forced tidal inlet system. Ph.D. Thesis, Delft University of Technology, The Netherlands, 2009.
4. Hung, N.T.; Cuong, V.D.; Hung, N.V.; Minh, N.Q. Study on seasonal changes of hydrodynamics regime in Nhat Le estuary, Quang Binh province. *J. Water Resour. Sci. Technol.* **2018**, *48*, 91–104.
5. Hung, N.T.; et al. National Research project "Research on erosion and accretion along the coast and estuaries from Quang Binh to Thua Thien Hue provinces, considering impacts of the reservoirs and proposing solutions", coded: KC08.16/16-20. Key Laboratory of River and Coastal Engineering, Vietnam, 2019.
6. Hung, N.T.; Cuong, V.D.; Hung, N.V.; Tuan, N.D. Factors controlling variation in sediment transport at Nhat Le estuary. Proceedings of the 10th International Conference on Asian and Pacific Coasts (APAC 2019) Hanoi, Vietnam, September 25-28, 2019.
7. Cuong, V.D.; Hung, N.T.; Hoa, T.D.; Thanh, N.T. Shoreline Changes and Sediment Transport along Nhat Le Coast, Vietnam. *Eng. Technol. Appl. Sci. Res.* **2024**, *14(2)*, 13493–13501.
8. Dan, N.L.; et al. Research project report "Study the current situation, identify the causes and propose solutions to prevent and control river estuary reclamation to open Nhat Le and Quang Binh channels". Vietnam Academy of Science and Technology, 2005.
9. Nghia, N.K.; et al. Project report "Investigation of current status of Nhat Le estuary in Quang Binh province and propose solutions to protect and complete exploitation". Vietnam Academy for Water Resources, Hanoi, 2009.
10. Cham, D.D.; et al. Research project report "Research on hydrodynamic mode (wave, flow) in Nhat Le coastal area - Quang Binh province using the MIKE 21 model". Institute of Geography, Ha Noi, 2017.
11. Tung, T.T.; Hung, T.D. Research on the application of Sentinel 2 images to assess the development of coastlines and changes in seabed topography in the area of Nhat Le estuary, Quang Binh. *J. Hydrometeorol.* **2023**, *746*, 1–11. https://doi.org/10.36335/VNJHM.2023(746).1-11.
12. Le, H.; Quang, N.; Tuan, V.; Nguyen, M.H. Analyzing river estuary changes using remote sensing images, a case study of Nhat Le river of Quang Binh Province. *TNU J. Sci. Technol.* **2022**, *227(3)*, 15–24. https://doi.org/10.34238/tnu-jst.5409.
13. Wave watch 3 global model: https://polar.ncep.noaa.gov/waves/download.shtml.

14. McFeeters, S.K. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *Int. J. Remote Sens.* **1996**, *17(7)*, 1425–1432. https://doi.org/10.1080/01431169608948714.
15. Huy, N.A.; Ty, T.V.; Duy, D.V.; Dat, P.T.; Man, T.K.; Dat, N.T.T.; Choi, Q.V. Longshore sediment transport rate at a pocket beach in Phu Quoc City, Kien Giang Province, Vietnam. *J. Hydro-Meteorol.* **2024**, *19*, 36–46. https://doi.org/10.36335/VNJHM.2024(19).36-46.
16. Deepika, B.; Avinash, K.; Jayappa, K.S. Shoreline change rate estimation and its forecast: remote sensing, geographical information system and statistics-based approach. *Int. J. Environ. Sci. Technol.* **2014**, *11*, 395–416.
17. Hedley, J.D.; Harborne A.R.; Mumby, P.J. Simple and robust removal of sun glint for mapping shallow-water benthos. *Int. J. Remote Sens.* **2005**, *26*, 2107–2112.
18. Stumpf, R.; Holderied K.; Sinclair, M. Determination of water depth with high-resolution satellite imagery over variable bottom types. *Limnol. Oceanogr.* **2003**, *48*, 547–556.
19. Thanh, N.T.; Son, N.H. Understanding shoreline and riverbank changes under the effect of meteorological forcings. Proceeding of the 10th International Conference on Asian and Pacific Coasts, Hanoi, Vietnam, Sep. 2019, pp. 1303–1310. https://doi.org/10.1007/978-981-15-0291-0177.
20. Tuan, Q.; Tin, C.; Quang, L.; Tuan, T. Historical monitoring of shoreline changes in the Cua Dai Estuary, Central Vietnam using multi-temporal remote sensing data. *Geosciences* **2017**, *7*, 72. Doi:10.3390/geosciences7030072.
21. Warrick, J.A.; Buscombe, D.; Vos, K.; Kenyon, H.; Ritchie, A.C.; Harley, M.D.; Janda, C.; L'Heureux, J.; Vitousek, S. Shoreline seasonality of California's beaches. *J. Geophys. Res.: Earth Surf.* **2025**, *130*, e2024JF007836. https://doi.org/10.1029/JF007836.
22. Castelle, B.; Ritz, A.; Marieu, V.; Nicolae Lerma, A.; Vandenhove, M. Primary drivers of multidecadal spatial and temporal patterns of shoreline change derived from optical satellite imagery. *Geomorphology* **2022**, *413*, 108360. https://doi.org/10.1016/j.geomorph.2022.108360.
23. Azzam, A.; Susilo, S.B. Estimating bathymetry using sentinel-2a for shallow-waters mapping: a case study in Kelapa Dua Island. *BIO Web Conf.* **2024**, *106*, 04001. https://doi.org/10.1051/bioconf/202410604001.
24. Tinh, D.X.; Tung, T.T.; Hung, T.D. An analysis of nearshore bathymetric changes in the Tien Chau estuary area, Phu Yen province, using Sentinel-2 images. *J. Hydrometeorol.* **2024**, *760*, 29–40. doi:10.36335/VNJHM.2024(760).29-40.
25. Tinh, D.X.; Tung, T.T.; Hung, T.D. The study of morphological development and the establishment of a correlation between the morphology of the Tien Chau river mouth and river dynamics factors. *J. Water Resour. Sci. Technol.* **2024**, *83*, 79–88.