MINISTRY OF EDUCATION AND TRAINING
MINISTRY OF AGRICULTURE AND ENVIRONMENT

VIETNAM ACADEMY FOR WATER RESOURCES

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STUDY ON THE MORPHOLOGICAL EVOLUTION OF THE NHAT LE ESTUARY

Field of engineering: Hydraulic Construction Engineering
Ref. code: 9 58 02 02

SUMMARY OF THE DOCTORAL DISSERTATION IN ENGINEERING

Ha Noi - 2025

The thesis was completed at:

Viet Nam Academy for Water Resources

Supervisors: Assoc.Prof. Dr. Nguyen Thanh Hung
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Reviewer #3: ....

The thesis will be defended in front of the Institute-level Doctoral Thesis Judging Committee meeting at the Vietnam Academy for Water Resourses, No 171 Tay Son street, Kim Lien ward, Ha Noi.
At .... on ...., 2025.

The dissertation can be accessed at the following libraries:

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INTRODUCTION

1. The Rationale for the Dissertation Topic

Vietnam has a 3254 km coastline with over 114 river mouths, averaging one every 20 km. Coastal estuarine zones are densely populated and play vital roles in seaport operation, urban development, tourism, aquaculture, and national defense. However, they are highly vulnerable to floods, erosion, sedimentation, saltwater intrusion, and environmental degradation. In particular, estuarine siltation obstructs flood discharge and navigation, causing severe socio-economic impacts.

Central Vietnam features narrow terrain, short and steep rivers, and a harsh monsoon climate with frequent floods and storms. Sediment from upstream accumulates at the river mouths, while strong northeasterly monsoon waves intensify siltation. Along the 1,800 km coast from Thanh Hoa to Binh Thuan, 52 estuaries exist, 45 of which are wave-dominated with sand spits forming arrow-shaped or recurved barriers. In such systems, wave action predominates, tides are micro-tidal, and river flows dominate mainly during the flood season. When sand spits extend, estuaries narrow, silt up, or even close completely.

Previous research has used field surveys, hydro-meteorological data analysis, GIS, remote sensing, and numerical modeling. Among these, numerical models provide detailed insights, yet long-term morphodynamic simulations remain challenging.

From both scientific and practical viewpoints, this dissertation investigates the morphodynamic evolution of wave-dominated estuaries with sand spits in Central Vietnam, focusing on the Nhat Le estuary (Quang Tri Province) as a representative case. It aims to determine the dominant hydrodynamic drivers of morphological change, develop a long-term simulation model, and propose integrated engineering solutions for estuarine stability and sustainable coastal development.

2. Research Objectives

- To investigate and quantify the impacts and relative contributions of key hydrodynamic factors to the morphological evolution of the estuary.

- To focuse on developing a robust long-term morphological simulation model for the estuary based on a combined approach of statistical analysis and advanced 2D numerical modeling, aiming to mitigate the drawback of prolonged computation time.

- To assess and recommend engineering solutions for estuarine regulation and stabilization, through the application of the long-term morphological simulation to analyze and evaluate their effectiveness.

3. Research Approach and Methodology

• *Research Approach*: This study applies a cause-to-effect approach, integrating theory and practice while extending previous research on estuarine morphology and stabilization. Using measured data, remote sensing images, and topographic surveys combined with the Delft3D model, the dissertation simulates hydrodynamics, sediment transport, and long-term morphological evolution of the Nhat Le estuary. Model results are validated with observations to assess reliability, analyze hydrodynamic influences, and propose effective stabilization solutions based on long-term simulations.

• *Research Methods*: (1) Field investigation, survey, and measurement; (2) Statistical analysis; (3) Remote sensing image and GIS analysis; (4) Numerical modeling; (5) Synthetic/Integrated analysis.

4. Scientific and Practical Significance of the Dissertation

• *Scientific Significance*: The dissertation develops a method combining data analysis and computational acceleration to enhance long-term morphodynamic simulation, identify key hydrodynamic drivers of morphological change, and provide a scientific basis for effective estuary regulation and sustainable socio-economic development.

• *Practical Significance*: The study on long-term estuarine morphological evolution identifies erosion-accretion trends, providing key data for coastal planning and protection. It develops a modeling approach for the Nhat Le estuary applicable to similar central Vietnamese estuaries, contributing to better management, sustainable development, and coastal community resilience.

CHAPTER 1. OVERVIEW OF RESEARCH ON MORPHOLOGICAL EVOLUTION AND STABILIZATION SOLUTIONS FOR ESTUARIES

1.1 General Introduction to Estuaries

1.1.1 Concepts and Classification of Estuaries

• *The concept of an estuary*:

- Estuaries is a complex natural geographic zone where freshwater from rivers and streams meets and mixes with saltwater from the ocean and is simultaneously influenced by both natural and anthropogenic factors. In this region, hydrodynamic processes occur in multiple dimensions and phases, involving continuous interactions among the river, the sea, and geological structures. Therefore, hydraulic phenomena in estuaries are highly dynamic, exhibiting both cyclical patterns and instability.

- A barred estuary refers to an estuary where a sandbar or sandspit has formed as a result of sediment accumulation driven by longshore currents, wave action, and other coastal processes, partially or completely obstructing the river mouth.

• *Classification of Estuaries*:

- Worldwide: Estuaries around the world are classified based on various criteria, such as tidal range (macrotidal, mesotidal, microtidal), geomorphology (deltaic, estuarine), sediment concentration, and the degree of salt-freshwater mixing. Some studies also classify them according to the relative dominance or interaction among river, wave, and tidal dynamics. In general, an integrated classification approach combining multiple factors is essential to support research and sustainable management of coastal estuarine systems.

- In Vietnam: Estuaries in Vietnam are mainly classified according to their planform morphology and the dominant hydrodynamic factor-whether fluvial or marine. Along the Central Coast, the most common type is the wave-dominated barred estuary (accounting for 45 out of 52 estuaries). This type exhibits the most pronounced and complex morphological variations, warranting detailed investigation.

1.1.2 Characteristics of barred estuary

• *Hydrodynamic characteristics*: Wave-dominated barred estuaries represent zones of complex interaction and competition between marine and fluvial dynamics. Seasonal and interannual variations in the intensity and correlation of these forces, compounded by human activities, result in highly variable, unpredictable, and sensitive hydrodynamic conditions.

• *Morphological characteristics*: The morphology of wave-dominated barred estuaries is typically unstable, cyclic, and strongly influenced by natural erosion-deposition processes. The evolution and migration of the estuary mouth generally occur in distinct stages: sandbar formation-mouth blockage-creation of a new mouth-closure of the old mouth-morphological restructuring.

1.2 Overview of Studies on Estuaries

1.2.1 Studies on Hydrodynamics and Morphological Evolution of Estuaries

• *Worldwide:* Studies have shown that sand spits in wave-dominated estuaries are primarily formed by longshore sediment transport under the hydrodynamic regime dominated by wave action. The roles of longshore currents and upstream sediment supply are crucial in determining the scale and orientation of spit development. These interactions not only shape the initial morphology but also control the temporal evolution of the sand spit.

• *In Vietnam:* Most studies have focused on wave-dominated barred estuaries along the Central Coast. These investigations have analyzed hydrodynamic mechanisms and morphological patterns, contributing significantly to the understanding of the natural development and transformation processes of estuaries.

1.2.2 Studies on Engineering Solutions for Estuary Regulation

• *Worldwide*: Developed countries began researching estuarine training works with physical models in the mid-19th century and advanced in the 20th century. Nations such as the U.S., U.K., France, Russia, China, the Netherlands, and Japan now use sediment transport models, remote sensing, and GIS to predict channel evolution and support estuary stabilization.

• *In Vietnam*: These studies have provided valuable scientific and practical insights, forming the foundation for designing solutions against estuarine siltation and shoreline erosion. Wave-dominated estuaries are commonly stabilized using jetties and training dikes to maintain navigation channels, ensure navigability, and protect coast.

1.3 Numerical Modeling Studies on Estuaries

• *Hydrodynamic and Sediment Transport Simulation*: Globally, hydrodynamic and sediment transport modeling began in the late 19th century, advancing rapidly between the 1930s and 1960s in Europe and the U.S. In Vietnam, it started in the 1960s and has grown quickly since 2000, becoming increasingly advanced and effective in recent years.

• *Short-term estuarine morphological change simulation:* Currently, numerous hydrodynamic models (e.g., MIKE, DELFT3D, TELEMAC, Hydro-GIS, MECCA) are widely applied worldwide and in Vietnam to simulate short-term estuarine morphology with high reliability, providing crucial data for effective estuary stabilization and management solutions.

• *Long-term estuarine morphological change simulation:* This remains a major challenge due to the long computational time required, with few related studies in Vietnam. Some simplify models to 1D or enhance hardware, but often at the cost of accuracy. More advanced approaches combine morphodynamic models (with acceleration factors) and statistical boundary analyses, showing strong potential for improving long-term estuarine simulations.

1.4 Evaluation of Achievements, Existing Gaps, and Research Directions of the Dissertation

• *Achievements and Remaining Limitations*:

- Achievements: Research on estuarine and coastal morphology has become more comprehensive and accurate. Short-term simulations clarify erosion-accretion patterns, while combined long-term approaches have yielded promising insights into estuarine evolution and stabilization solutions.

- Remaining limitations: Long-term morphodynamic simulations remain challenging due to the high computational demands of 2D-3D models. Most studies focus on tidal and wave effects, while river discharge and storm surge impacts-critical for estuaries in the Central Coast of Vietnam are still insufficiently addressed..

• *Research Directions of the Dissertation:*

- Assessing and clarifying the influence and dominance of individual dynamic factors on estuarine morphodynamics: Using morphodynamic simulation methods, the dissertation performs model runs under different boundary conditions to isolate individual driving factors. Based on the resulting patterns of erosion and accretion, the relative contribution of each dynamic factor to the morphodynamic evolution of the Nhat Le estuary is quantitatively assessed.

- Developing an approach for long-term estuarine morphodynamic simulation: This study explores the combination of morphodynamic modeling (with a morphological acceleration factor - Mf) and analytical methods (statistical and harmonic analyses) to generate composite boundary conditions, thereby shortening the computational time for long-term morphodynamic simulations.

- Proposing engineering solutions for overall stabilization of the Nhat Le estuary: The study investigates spatial configurations of stabilization structures, focusing particularly on the influence of jetty length on the estuary's flood discharge capacity. The effectiveness and impacts of the proposed engineering alternatives are evaluated through long-term morphodynamic simulations.

1.5 Introduction to the Nhat Le Estuary

The Nhat Le estuary is located in Dong Hoi ward, Quang Tri province. The river mouth flows into the East Sea in a northeastward direction, while the coastline runs northwest-southeast. As a result, this coastal area is frequently subjected to severe erosion caused by large waves during the northeast monsoon season, when waves approach the shore almost perpendicularly. Meanwhile, the estuary itself experiences significant sedimentation and highly complex channel variations.

1.6 Chapter 1 Summary

Chapter 1 reviews global and Vietnamese estuarine studies, noting early advances in hydrodynamic-morphological modeling but limited long-term research mainly addressing tides and waves. In Vietnam, studies are mostly short-term or simplified, constrained by data and computation. Thus, this dissertation's long-term morphodynamic modeling and stabilization solutions for Nhat Le estuary offer a novel contribution.

CHAPTER 2. SCIENTIFIC BASIS AND RESEARCH METHODOLOGY

2.1 Meteorological and Hydro-Marine Conditions of the Study Area

The Nhat Le river basin lies within a tropical monsoon climate zone, characterized by two distinct seasons: the rainy season (September-March) and the dry season (April-August).

River flow: Flow of the river is concentrated mainly during the flood season (September-December), accounting for 75-77% of the annual discharge. In contrast, the dry-season flow is very low, averaging only 15-20 $l/s \cdot km^2$. Floods occur rapidly and intensely, typically in four stages: the early-summer flood (May-June), the early flood (July-August), the main flood (September-November), and the late flood (December-January). Major floods have been recorded at Kien Giang (1979: 2640 m^3/s, recurrence 0,2%) and at Tam Lu (1971: recurrence 3%).

Tides: The area is influenced by an irregular semidiurnal tide, with tidal ranges varying from 0.5-0.6 m during neap tides to 1.2-1.6 m during spring tides.

Waves: Wave conditions are governed by the monsoon, with two distinct wave seasons. During the northeast monsoon (October-March), waves are high, with an average height of 0.8-1.2 m and peaks reaching 4.0-4.5 m. During the southwest monsoon (May-August), waves are smaller, averaging 0.6-0.7 m. During typhoons, wave heights can reach 5-8 m. The regional wave climate is characterized by two dominant directions.

Storm surge and seasonal water level variation: Storm surges can reach heights of 2.5-3.0 m and last from 3 to 24 hours. Seasonal water level fluctuations range from 30 to 40 cm and can persist for several days. When combined with large waves during the northeast monsoon, these conditions often cause severe coastal erosion.

2.2 Scientific Basis for Long-Term Morphological Evolution Study of the Estuary

2.2.1 Seasonal Variations of Water Level, Wave, and River Discharge at the Estuary

During the northeast monsoon (September-April), Nhat Le estuary faces strong hydrodynamic forces with large waves and high water levels. From September–December, floods and waves cause intense morphological change; from January-April, reduced discharge but strong waves sustain it. In the southwest monsoon (May-August), weaker waves and low flow create relatively stable morphology with slow sedimentation and erosion.

2.2.2 Scientific Basis of Mathematical Equations in the Delft3D Model

The dissertation uses the Delft3D model (Deltares, Netherlands) in a twodimensional (2DH) configuration to simulate hydrodynamics, sediment transport, and morphological evolution at the Nhật Lệ estuary. Delft3D includes three coupled modules: FLOW (hydrodynamics), WAVE (waves, SWAN-based), and SED (sediment transport), allowing interactive simulation of waves, currents, and sediment dynamics. Sediment transport, for both suspended and bed loads, is calculated using the advection–diffusion approach and the Van Rijn (1993) formula, with continuous bed-level updates. To accelerate long-term simulations, the model applies a Morphological Acceleration Factor (MorFac or Mf), which multiplies sediment transport rates based on the assumption that morphology evolves more slowly than hydrodynamics. For instance, Mf = 10 represents 140 days of change in 14 days of computation, while Mf = 26 simulates one year within a single tidal cycle.

2.2.3 Combined Approach of Statistical Techniques and Numerical Modeling

In long-term morphological simulations, using the full multi-year dataset is impractical due to high computational costs. Thus, boundary conditions (waves, tides, discharge, sediment) are statistically reduced to representative conditions. Offshore wave data (Hsig, Tp, MWD) are grouped by season, direction, and frequency; water levels are reconstructed from observations and TPXO7.2; river discharge and sediment load (from MIKE Flood and SWAT) are statistically analyzed for flood and dry seasons. A 2DH model combined with the MorFac coefficient simulates long-term morphology of Nhat Le estuary, accelerating bed evolution while maintaining accuracy (Lesser et al., 2004; Roelvink, 2006).

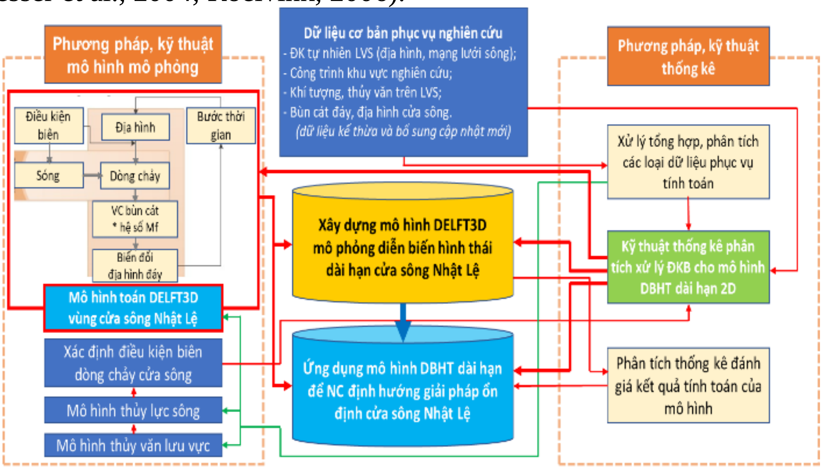


Figure 2.5: Schematic diagram of the combination between statistical

methods and numerical modeling

This method assumes morphological changes occur more slowly than hydrodynamic processes, allowing time reduction via the Morphological Acceleration Factor (Mf). Flow, sediment transport, and bed updates are computed simultaneously, capturing two-way interactions. However, excessive Mf may cause errors under extreme conditions. The dissertation uses a fixed MorFac and representative one-year boundary conditions to balance accuracy and efficiency for 5-10 year simulations.

2.3 Research Methodology for Long-Term Morphological Evolution of the Estuary

2.3.1 Remote Sensing Image and GIS Analysis

- Shoreline change analysis: Satellite images were collected, enhanced in quality, and geometrically corrected. The Normalized Difference Water Index (NDWI) was computed to separate land and water areas, enabling shoreline extraction. The extracted shorelines were then refined and edited in ArcGIS, and shoreline change analysis was performed using DSAS (Digital Shoreline Analysis System) with two key indicators: SCE (Shoreline Change Envelope) and LRR (Linear Regression Rate).

- Satellite-derived bathymetry for the Nhat Le estuary using Sentinel-2 imagery combined with depth measurement data: The images were processed to remove terrestrial topography and correct for reflectance effects. A depth index was calculated, and a correlation equation was established (R^2 = 0.767), enabling the bathymetric interpretation of the estuary for different periods between 2015 and 2024.

2.3.2 Hydrological, Hydraulic, and Sediment Transport Modeling for the Study Area

The long-term morphodynamic study of the Nhat Le estuary requires a continuous input dataset of at least 20 years to capture the 11-year hydrological and 19-year oceanographic cycles. Due to the lack of field measurements, the dissertation generated synthetic data using numerical models: SWAT to compute runoff and sediment load from rainfall, Mike Flood to determine river discharge at the estuary, and Litpack to simulate longshore sediment transport. The Delft3D (2DH) model serves as the core framework, simulating the hydrodynamics, sediment transport, and morphological evolution of the estuary.

2.3.3 Setting Up Delft3D Model for the Study Area

Figure 2.10: Delft3D model domain established for the Nhat Le estuary area

• *Model domain and boundary conditions*: The Delft3D grid for the Nhat Le estuary extends 12 km upstream, 40 km offshore, and 40 km along the coast, with resolutions of 10-30 m inside the estuary and 50-1,000 m offshore to ensure accurate hydrodynamic and sediment transport simulations. Boundary conditions include river discharge (from field surveys or Mike Flood), tidal levels (TPXO7.2 and Dong Hoi observations), waves and wind (Wave Watch III), and fluvial sediment (SWAT model). A zero sediment condition is applied offshore, while Neumann conditions are set along the coastline.

• *Model calibration and validation:* Using survey data from project KC08.16/16-20, including field campaigns in April and October 2018, the hydrodynamic model was calibrated with water level, wave, and current measurements, yielding NSE values of 0.6-0.89 and RMSE of 0.06-0.21, showing good agreement with observations. Sediment transport and morphological change calibration used overlaid bathymetric maps to compare erosion-deposition across four characteristic zones. Results matched field observations, with erosion along the northern bank and inner estuary, and deposition along the southern bank and outer channel. The model demonstrated reliable accuracy, ready for scenario simulations.

2.4 Chapter 2 Summary

In Chapter 2, the dissertation analyzes meteorological and hydro–oceanographic conditions, with a focus on the seasonal variability of waves, water levels, and river discharge at the Nhat Le estuary. It presents the theoretical basis of the Delft3D model, the morphological acceleration factor (MorFac or Mf), and the combined approach morphodynamic modeling with statistical analysis to construct representative boundary conditions, thereby reducing computational time while maintaining reliability. Remote sensing and GIS techniques are employed to analyze shoreline changes, bathymetric evolution, and to provide model input data. The Delft3D model is used to simulate hydrodynamics, sediment transport, and to develop a long-term morphodynamic modeling approach for the Nhat Le estuary.

CHAPTER 3. STUDY ON THE MORPHOLOGICAL EVOLUTION OF THE NHAT LE ESTUARY

3.1 Selection of the Analysis Period for the Morphological Evolution of the Nhat Le Estuary

The dissertation selects two periods for analyzing the morphodynamic evolution of the Nhat Le estuary (1999–2009 and 2009–2019) based on both scientific and practical considerations, including: (1) The hydrological - oceanographic cycles (11-19 years), which reflect variations in river discharge, tides, and waves; (2) The availability of comprehensive observational data, including bathymetric maps and remote sensing imagery (Landsat, Sentinel); (3) The impact of human interventions, particularly the construction of the My Canh revetment (2009) and the dredging of the navigation channel (2020).

3.2 Morphological Evolution of the Nhat Le Estuary Based on Observational Data

3.2.1 Shoreline Changes in the Nhat Le Estuary Area

• *Seasonal shoreline variation:*

Based on the hydro–oceanographic seasonal characteristics, Landsat and Sentinel-2 images were used to interpret the shoreline during two seasons: winter (January-April, September-December) and summer (May-August). During 1999-2009, the sand spits developed strongly, particularly the southern spit, which elongated and narrowed the estuary mouth. In 2009-2019, the sand spits became smaller, and the mouth widened. From 2020-2024, the northern spit disappeared, while the southern spit narrowed and migrated landward.

• *Evolution of the southern sand spit at the Nhat Le estuary:*

Key parameters were extracted, including annual maximum river discharge (Qmax), mouth width (B), spit length (L), and spit orientation angle (φ) from the final satellite image of each season. Results show that between 2009-2019 compared to 1999-2009, Qmax increased (from 1,941 to 2,145 m^3/s), while B decreased (from 258 to 199 m), L shortened (from 218-269 m to 132-160 m), and φ decreased, indicating a gradual seaward rotation of the southern spit.

• *Shoreline change rate:*

A total of 180 transects spaced 100 m apart were used to analyze shoreline change during 1999-2009 and 2009-2019, using the SCE (Shoreline Change Envelope) and LRR (Linear Regression Rate) indices. Results show that the area near the estuary experienced strong shoreline dynamics, especially along the northern 4 km and southern 2.5 km coastal segments. During 2009-2019, erosion intensified-most notably in Hai Thanh, Quang Phu, and Bao Ninh, with average rates of 2–4 m/year.

• *Coastal erosion-accretion dynamics:*

Using remote sensing and GIS, coastal changes along the Nhat Le shoreline were analyzed. During 1999-2009, accretion dominated, with the largest accretion areas of 10.76 ha (north) and 2.52 ha (south). The maximum accretion rates reached 10.12 m/year (north) and 28.44 m/year (south), while erosion mainly occurred on the southern shore (1.68 ha). In contrast, during 2009-2019, erosion increased significantly, reaching 4.31 ha (north) and 6.59 ha (south). Although the shoreline retreated, sediment deposition inside the estuary continued, narrowing the estuary mouth in planform.

3.2.2 Evolution of the Main Channel at the Nhat Le Estuary

The formation and unstable evolution of the northern sand spit and the southern sand arrow cause the main inlet channel of the Nhat Le estuary to fluctuate significantly, sweeping an angle of approximately 60°, from north-northeast (NNE) to east-northeast (ENE). During 1999-2009, the deep channel was oriented north–northeast; from 2009-019, it shifted toward northeast-east-northeast; and in 2020-2024, it gradually migrated toward the east.The overall trend indicates a progressive eastward migration of the main channel through the Nhat Le estuary.

3.2.3 Erosion and Accretion Dynamics in the Nhat Le Estuary Area

Based on bathymetric survey data, the study compared overlaid bathymetric maps from the periods 2005-2007, 2009-2015, 2015-2019, and 2009-2019 to assess erosion-deposition dynamics at the Nhat Le estuary. Results show that the estuary zone exhibits a strong accretion trend, with a sediment deposition volume of approximately 812,000 m^3 during 2009-2015, while the northern and southern coastal zones are predominantly erosional. Overall, during the period 2005-2019, the estuary area accreted, whereas the coastal zone experienced significant erosion.

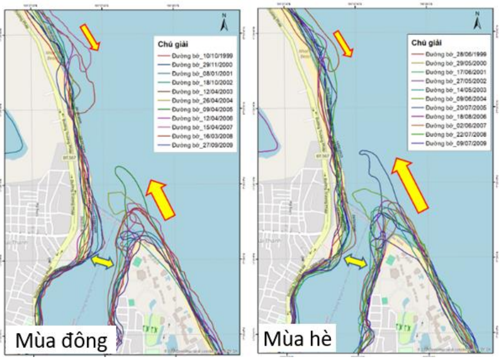


Figure 3.1-a: Shoreline changes during the period 1999-2009

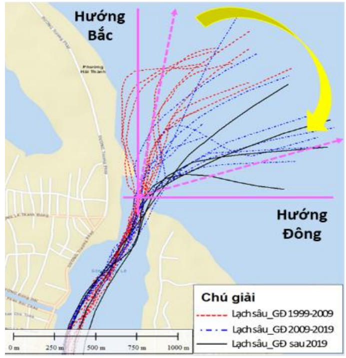


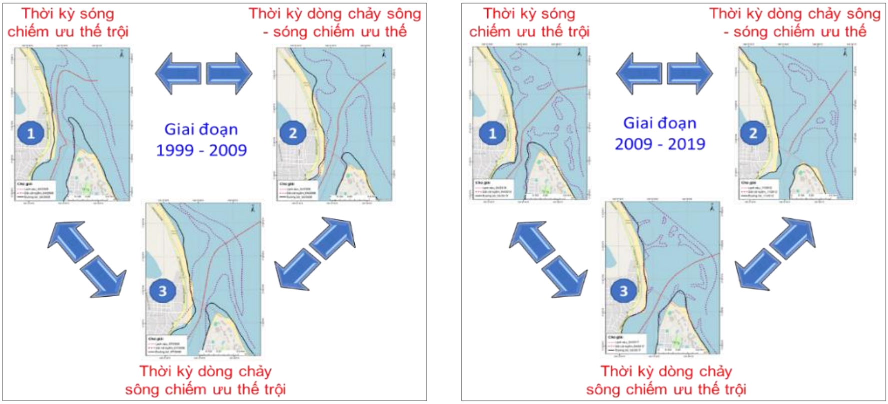
Figure 3.8: Summary of the main channel evolution

3.2.4 Synthesis of Morphological Evolution Trends Based on Observational Data

From bathymetric survey data and Sentinel imagery, a comprehensive dataset of shoreline, submerged sandbars, and deep channel paths was compiled to assess the morphological evolution of the Nhat Le estuary. The estuary's morphology is primarily controlled by river discharge and wave conditions. When both discharge and wave energy are low (e.g., in 2005 and 2015), the southern sand spit develops strongly, pushing the deep channel northward and narrowing the estuary mouth. In contrast, during periods of high discharge and strong waves (e.g., 2006, 2009, 2012, and 2017), the southern sand spit shortens, the estuary widens, the deep channel shifts toward the center, and the offshore sandbar moves further seaward.

3.2.5 Relationship Between Morphological Changes and Hydro-Marine Conditions of the Nhat Le Estuary Area

The dissertation has summarized into a diagram the morphological evolution cycle of Nhat Le estuary during 1999-2019 and 2009-2019. These cycles exhibit three basic forms characteristic of different periods: (1) a wave-dominated period, (2) a period with both river flow and waves co-dominating, and (3) a river-flow-dominated period. In the 2009-2019 period, the estuary's morphology shows a shorter sand spit on the southern bank, oriented seaward, with the main channel shifting toward the center of the estuary. The estuarine shoals have narrowed and are more dispersed, forming alternating accretion and erosion zones compared to the previous period.



a) Period 1999 - 2009 *b) Period 2009 - 2019*

Figure 3.13: Schematic diagram of the morphological evolution cycle of the Nhat Le estuary from 1999 to 2019

3.3 Assessment of the Impact and Dominance of Dynamic Factors on the Long-Term Morphological Evolution of the Nhat Le Estuary

Estuarine and coastal morphology changes continuously under riverine and marine forces operating at two time scales: long-term (waves, monsoons, tides, seasonal water levels, river discharge) and short-term (storms, surges, floods). Section 3.3 analyzes their impacts and identifies boundary factors for long-term morphological simulation of the Nhat Le estuary.

3.3.1 Analysis and Selection of Scenarios

The dissertation evaluates the impact and dominance of dynamic factors (waves, tides, local winds, river discharge, and seasonal water level variations) on the morphological changes of Nhat Le estuary by calculating the annual sediment erosion–accretion using the Delft3D model, selecting 2018 as the study year due to the availability of synchronized data. Hourly water level measurements were analyzed by separating tidal components from seasonal water level variations, with seasonal fluctuation amplitudes of 20-40 cm (low in summer, high in winter). The study simulates five scenarios: the baseline scenario KB1 including all five factors, and four scenarios each excluding one factor in turn. The tidal factor, as a fundamental background factor with cyclic variations, is included in all scenarios.

3.3.2 Computation of Erosion and Accretion Under Various Scenarios

The simulation results of the five scenarios show that scenario KB2 (without waves) differs most significantly from the baseline scenario KB1 in terms of erosion–accretion trends. Scenarios KB3, KB4, and KB5 (excluding local winds, river discharge, and seasonal water level variations, respectively) show little difference compared to KB1 (all five factors included). In KB2, seabed morphology fluctuates primarily due to river discharge, forming a closed, arcuate estuarine shoal. The sediment erosion–accretion volume in KB2 is the smallest compared to KB1 and the other scenarios.

3.3.3 Evaluation of the Impact and Dominance of Dynamic Factors

The impacts of dynamic factors were assessed by comparing sediment erosion–accretion across five scenarios. Waves are the most dominant, with their removal reducing erosion-accretion by 48.6-69.1% in the estuary and 94.4-98.1% along the coast. River discharge also significantly influences erosion-accretion (13-14% reduction). Seasonal water level variations moderately affect morphology (6-9% reduction), while local winds have minimal impact (0.9-2.4%). Overall, waves and river discharge are the primary drivers, with seasonal water level changes also notably contributing to the long-term morphological evolution of the Nhat Le estuary.

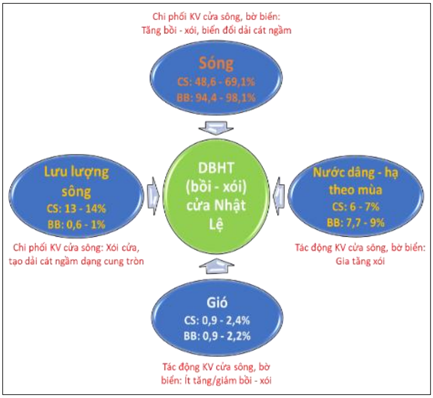


Figure 3.16: Diagram illustrating the impact and dominance of dynamic factors on the long-term morphological evolution of Nhat Le estuary

3.4 Research on Developing a Long-Term Morphological Simulation Model for the Nhat Le Estuary

Based on the scientific foundation of the combined approach between statistical techniques and numerical modeling presented in Section 2.2.3 of Chapter 2, and the main dynamic factors identified in Section 3.3, the dissertation specifically investigates the approach for developing a long-term morphological simulation model for Nhat Le estuary.

3.4.1 Data Processing for Model Boundary Conditions

• *Statistical analysis for processing wave boundary data:* A 45-year wave dataset (1979-2024) from Wave Watch III offshore was used. Statistical analyses were conducted on the frequency of occurrence of three wave parameters-height, direction, and period for each month of the year. These results were used to generate a representative annual climate wave series as boundary conditions for the long-term morphological simulation of the estuary. The statistical analysis shows clear seasonal variations: Northeast monsoon season (October-March): waves from NNW-ENE-ESE, with the highest heights and periods in October-January. Southwest monsoon season

(May-August): waves from NNW-SE and NNE-SSE, with the smallest heights and periods in May-August. Transitional months (April and September): waves from three main directions, with September waves stronger than April.

• *Harmonic analysis for processing water level boundary data:* A 35-year hourly water level record (1990-2024) at Dong Hoi station (Nhat Le estuary) was used to establish water level boundaries for the long-term morphological model. Using harmonic analysis, water levels were separated into two components: tidal oscillations (diurnal, semidiurnal tides, and long-period seasonal waves) and non-tidal oscillations (water level rise due to wind, storms, waves, and floods). The non-tidal, irregular component was removed. Results, a total of 69 harmonic constants were identified, from which 10 main constants (Q1, O1, P1, K1, N2, M2, S2, K2, SA, SSA) plus the mean level constant A0 were selected to predict water levels as model boundary conditions. Given the wide spatial domain (≈40 km), A0 and SA/SSA were combined with the global tidal constants from TOPEX to ensure both regional characteristics and continuity of tidal variations across the model boundaries.

• *Statistical analysis for river discharge and sediment boundary data:* Due to the lack of gauging stations near Nhat Le estuary (stations at Kien Giang and Tam Lu upstream ceased operation in the 1980s), the dissertation used the SWAT and Mike Flood models (inherited and updated from project KC08.16/16-20) to simulate hydrology, hydraulics, and sediment transport. This approach generated a 35-year series (1990-2024) of daily-averaged river discharge and suspended sediment concentration at the estuary. Results, peak discharges range from < 1000 m^3/s in dry years to 2,000-4,000 m^3/s in wet years. Suspended sediment concentrations vary from < 50 g/m^3 in low period flow to ≈5 kg/m^3 during major floods. This dataset was statistically analyzed, and median values were selected as boundary conditions for the long-term morphological simulation model.

3.4.2 Hydrodynamics Simulation of the Nhat Le Estuary Using the Long-Term Morphological Evolution Model

To accurately simulate the estuarine morphological evolution, the model must first reproduce the hydrodynamic regime of the estuary. The dissertation ran and evaluated the model using the one-year boundary conditions established in Section 3.4.1. The results show that the model effectively captures seasonal hydrodynamic variations in the Nhat Le estuary.

• *Wave characteristics:* During the Northeast monsoon season, waves primarily come from the NE direction, with nearshore heights of 0.7-1.1 m along the northern coast and 0.5-0.8 m along the southern coast. Strong wave refraction causes energy convergence along the northern coast, leading to intense erosion, while the southern coast is less affected and tends to accumulate sediment. Nearshore currents during this season flow mainly from north to south, controlling sediment transport and contributing to northern coast erosion. During the Southwest monsoon season, waves from the N direction are weaker, more evenly distributed, and less convergent, primarily causing deposition around the southern sand spit. Nearshore currents reverse from south to north, temporarily reducing the erosion left by the Northeast monsoon season..

• *Flow characteristics:* During the Northeast monsoon season, the main current flows southeast with velocities exceeding 0.5 m/s, extending offshore. Nearshore currents develop at 0.2-0.35 m/s, causing erosion. During the Southwest monsoon season, currents weaken and shift northward under the influence of N direction waves. Along the northern bank, nearshore currents reverse from south to north, reducing erosion, while a weak converging current forms near the southern estuary, enhancing sediment deposition. These nearshore current variations clearly reflect the combined influence of monsoon winds, waves, and shoreline topography, controlling the estuarine erosion-accretion processes.

3.4.3 Long-Term Morphological Simulation of the Nhat Le Estuary

The Delft3D model was established with boundary conditions fully reflecting seasonal hydrodynamic and oceanographic variations as described above, and was then extended to simulate morphological evolution over 5-10 year periods. Since the boundary dataset spans only one year, a morphological acceleration factor (MorFac, Mf) ranging from 5 to 10 was applied when simulating the 5-10 year evolution. This approach allows the annual boundary sequence to be repeated while accelerating the morphological change by the MorFac value at each simulation time step, ensuring that long-term trends are captured. Comparison of the model results with field measurements (2009-2015 and 2009-2019) shows that the model reproduces erosion-accretion trends well, particularly in areas with strong morphological changes. In the estuarine zone, the ratio of simulated to surveyed sediment volumes (V_{MH}/V_{KS}, where V_{MH} is the volume from the model and V_{KS} is from surveys) reaches 0.83 (672,855/811,785 m³) over 5 years and 0.86 (1,022,888/1,195,480 m³) over 10 years, indicating good agreement in both trend and magnitude. Ratios in other areas (river channel, northern and southern banks) are lower. These results confirm the feasibility of the long-term morphological simulation model for Nhat Le estuary.

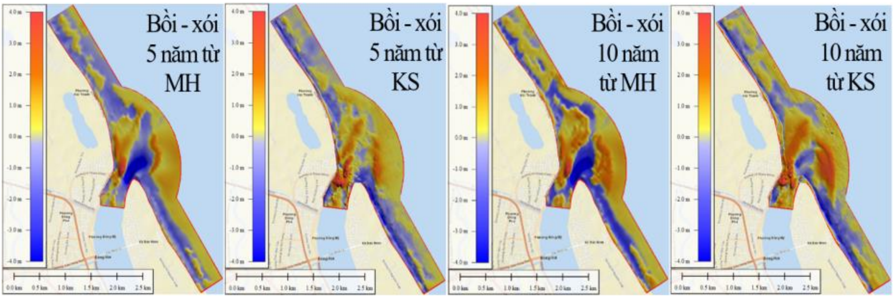


Figure 3.29: Comparison of sediment erosion–accretion between model results and surveyed topography

3.4.4 Proposed Approach for Developing a Long-Term Morphological Simulation Model

Based on the long-term morphological simulation results (5-10 years) for 2009-2019, the dissertation proposes an approach for developing a long-term morphological model for Nhat Le estuary with the following main steps:

• *Boundary condition analysis:*

- Wave boundary: One-year climate wave series, statistically analyzed to determine representative climate waves.

- Water level boundary: One-year hourly water level series, harmonic tidal analysis to determine tidal constants and seasonal water level variations.

- River discharge boundary: One-year daily-averaged river discharge series, statistically analyzed to determine median values.

- Sediment boundary: One-year daily-averaged suspended sediment concentration series, statistically analyzed to determine median values.

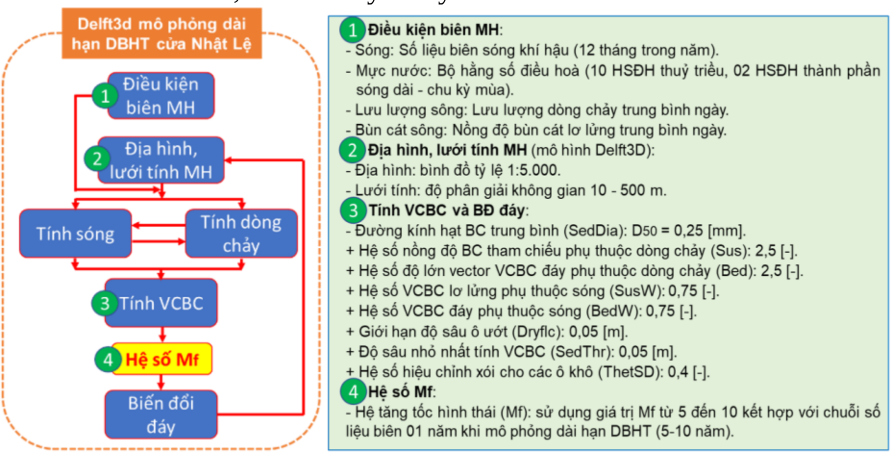


Figure 3.31: Flowchart of the approach for developing a long-term morphological simulation model of Nhat Le estuary

• *Model setup:*

Apply Delft3D with a morphological acceleration factor (Mf). Computational grid resolution of 10-20 m in the estuary, gradually increasing to 500 m offshore, ensuring both accuracy and reasonable computation time.

• *Simulation period:*

Choose 5-10 years, matching the morphological trend and computational capacity of a high-performance personal computer.

3.5 Chapter 3 Summary

Chapter 3 analyzed the morphological evolution of the Nhat Le estuary using multi-year bathymetric data, remote sensing, and Delft3D simulations. Results reveal complex erosion–accretion dynamics driven by waves and seasonal river discharge. The southern sand spit shortened from 218-269 m (1999-2009) to 132-160 m (2009-2019). Simulations confirmed waves as the dominant factor (48.6-69.1% in the estuary, 94.4-98.1% along the coast), followed by river discharge and seasonal water level changes. A long-term simulation method (5-10 years) using a one-year boundary dataset with MorFac = 5-10 effectively reproduced morphological trends and channel migration, forming the scientific foundation for stabilization solutions proposed in Chapter 4.

CHAPTER 4. ORIENTATION OF STABILIZATION SOLUTIONS FOR THE NHAT LE ESTUARY

4.1 Objectives and Requirements for Regulating the Nhat Le Estuary

• *Objectives of the estuary regulation*: Stabilize navigation channels and maintain sufficient depth for waterway traffic; ensure flood discharge capacity (return period P = 5%); protect and restore beaches, reduce erosion, and preserve the environment and landscape of the estuarine area.

• *Requirements for regulating Nhat Le estuary*: Functionally and structurally, Nhat Le is a shallow, sand-spit estuary with strong seasonal fluctuations causing channel siltation and obstructed flood discharge. The proposed solution is a jetty system on both banks to guide flow, stabilize navigation, and reduce dredging. Jetties should extend beyond the breaker zone, ensure flood discharge for a 5% return period, and consider landscape and tourism aspects. Severe shoreline erosion on both coasts requires submerged breakwaters combined with groins for coastal protection and landscape preservation.

4.2 Impacts of Jetty Spatial Layout on the Flood Discharge Capacity of the Estuary

The impact of jetty lengths on flood discharge at Nhat Le estuary were evaluated using the Delft3D model. With a fixed width of 350 m between the jetties (bounded by Truong Phap Road and SunSpa-My Canh seawall), optimal jetty length ensuring adequate flood discharge was determined.

4.2.1 Preliminary Layout Schemes for the Jetties

The Nhat Le estuary is narrow, hindering flood discharge; thus, the jetty spacing should not be smaller than the natural width. The estuary alignment remains fixed, while jetty length varies from 250 m to 1000 m in 100 m increments, forming eight scenarios. Each scenario is simulated for a 5% return period flood to assess impacts using 11 monitoring points (P1-P11) for water level and velocity from Nhat Le Bridge to the river mouth.

4.2.2 Impact of the Jetties on Flood Discharge Capacity

• *Flood water level change:* Analysis of maximum water levels (Hmax) at 11 points along Nhat Le river shows that as length of the jetties increases from PA0 to PA1000 m, water levels tend to rise, becoming pronounced from PA650 m onward. At P1-P4 (near Nhat Le bridge), Hmax increases by 0.25-0.27 m; P5-P8 increases by 0.26-0.30 m, reflecting reduced flood discharge efficiency. P10 (at mouth) rises the most, by 0.91 m (from 1.10 m to 2.01 m) due to water accumulation, while P11 (outside the mouth) rises slightly by 0.19 m. Regression analysis indicates that Hmax increases sharply up to PA750 m and then gradually stabilizes.

• *Flood current velocity change*: Analysis of flood flow fields under different jetties layouts shows that dike length strongly affects flood discharge and sediment transport. At PA0 (no jetties), flow is widely dispersed, creating local eddies and reducing discharge efficiency. Scenarios PA250-PA450 m begin to guide the flow but still show dispersion past the estuary. From PA550-PA750 m, flow stabilizes, with velocities concentrated along the offshore axis, reducing eddies and enhancing sediment transport. However, PA850-PA1000 m causes excessive channelization, forming local peak velocities between the two dikes. Vmax analysis shows slight decreases at P1-P4 (0.08-0.09 m/s), little change at P5-P8, sharp decreases near 1 m/s at P9-P10, and a sudden increase at P11 from 2.31 to 4.50 m/s, indicating that a jetties length around 750 m is optimal for flood discharge.

• *Relationship between flood water level, flow velocity, and NCGS jetty length*: Correlation analysis between maximum flood water level (H_i/H_0 max) and velocity (V_i/V_0 max) at P7-P11 shows a clear dependence on jetty length. In the inner estuary (P7-P9), a strong negative linear correlation (R^2 = 0.82-0.88) indicates that as water level rises, flow velocity decreases. At P10 (near the mouth), this correlation is strongest (R^2 = 0.99), reflecting flow dispersion at higher water levels. Conversely, at P11 (outer), the correlation becomes positive (R^2 = 0.41), as rising water levels enhance velocity due to the river-sea gradient, though this is less consistent. The results suggest that optimal jetty length should balance water level rise and flood discharge efficiency.

4.3 Proposed Stabilization Solutions for the Nhat Le Estuary

Based on the determined jetties length, the dissertation studies the detailed layout of the engineering structures, analyzes, and proposes appropriate regulation measures to stabilize the overall Nhat Le estuary area.

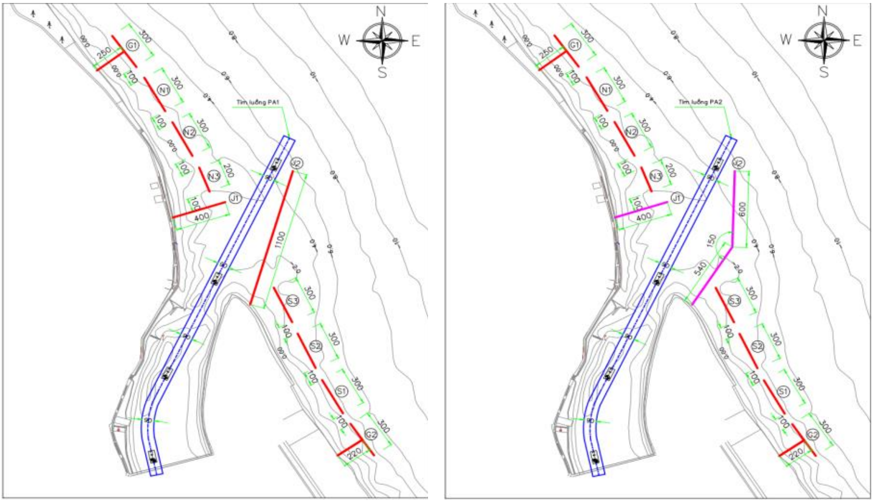
4.3.1 Layout of the Structural System for Stabilizing the Nhat Le Estuary

• *Proposed jetties to stabilize the navigation channel*: Analysis shows that to stabilize the Nhat Le estuary and eliminate the obstructing shoal, jetties must extend at least 750 m. However, longer jetties can elevate flood water levels by restricting direct sea discharge. Therefore, for jetties ≥ 750 m, alignment and spacing should be optimized to enhance flood conveyance and minimize inundation risk. Morphological analysis reveals strong channel, sand spit, and shoal variability. With a design channel bottom of −6.3 m and shoals at -2 to -4 m, jetties must extend beyond the shoals. Two options are proposed: PA1 with 400 m north jetty, 1,100 m south jetty at 45°; PA2 with the same north jetty, segmented south jetty (540 m at 70°, 600 m wave section), crest +3.0 m.

Analysis shows that to stabilize the Nhat Le estuary and remove the obstructing shoal, the jetties should extend at least 750 m. However, longer jetties may raise flood levels by limiting direct sea discharge. Thus, for jetties ≥ 750 m, alignment and spacing must be optimized to enhance flood conveyance and reduce inundation risk. Morphological analysis reveals strong channel, sand spit, and shoal variability. With a design channel bottom of -6.3 m and shoals -2 to -4 m, jetties must extend beyond the shoals. Two options are proposed: PA1 with 400 m north jetty, 1,100 m south jetty at 45°; PA2 with the same north jetty, two-segment south jetty (540 m at 70°, 600 m wave section), crest +3.0 m.

• *Proposed submerged wave-reducing dikes to stabilize adjacent coasts*: The dissertation proposes a system of detached submerged breakwaters to promote sediment deposition and stabilize both northern and southern coasts of the Nhat Le estuary. Design locations and scales follow TCVN 9901:2023, previous studies, and longshore sediment transport widths (220-250 m, depth ≈ -5 m) estimated by the Litpack model. North coast (Bau Tro): 1.4 km protection line with three breakwaters (2 × 300 m, 1 × 200 m), spaced 100 m, 200-250 m offshore, crest +0.5 m; one T-groin (wing 300 m, stem 220 m, crest +0.5 m). South coast (Bao Ninh): 1.5 km line with three 300 m breakwaters, same spacing and crest, plus one T-groin (wing 300 m, stem 230 m, crest +0.5 m).

• *Overall layout*: Combining the jetties schemes with the submerged breakewater scheme results in two spatial arrangements of the estuarine stabilization system, denoted PA1-BW and PA2-BW.



a) PA1-BW scheme *b) PA2-BW scheme*

Figure 4.11: Overall layout of the engineering structures at Nhat Le estuary

4.3.2 Evaluation of the Structure's Impact on River Flood Discharge Capacity

• *Change in flood water level*: Both alternatives PA1 and PA2 increase Hmax compared to the existing condition (PA0), especially in the upstream area (P1-P6). PA1 causes a stronger impact, for example, at P1 point, Hmax rises from 2.99 m (PA0) to 3.10 m (PA1) and 3.07 m (PA2). In the midstream section (P5-P7), the increase is also noticeable, such as at P7, from 2.70 m to 2.83 m (PA1) and 2.79 m (PA2). In the estuary area (P9-P11), the increase is smaller, but P10 is the most sensitive point, where Hmax rises from 1.10 m to 1.76 m (PA1) and 1.53 m (PA2).

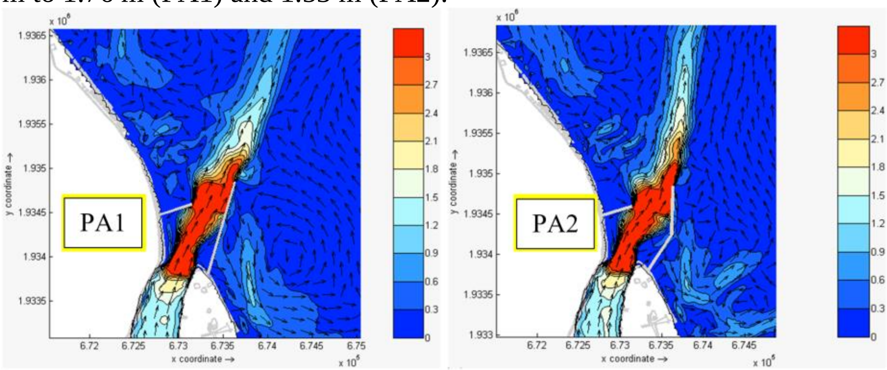


Figure 4.13: Changes in flood flow velocity under different jetty layout

• *Change in flood current velocity*: There is a clear difference between the two jetty alternatives. In PA1, the flow becomes concentrated and strongly accelerated (velocity > 2.7 m/s) but is deflected toward the southern bank, creating local vortices and posing a scour risk at the jetty head. In contrast, PA2 provides a more stable flow direction, aligned straight toward the sea, with high-velocity zones distributed more evenly, reducing turbulence and weakening vortices. Owing to its wider flood discharge area, PA2 proves to be more effective in controlling and distributing the flow.

4.3.3 Assessment of the Impact of the Structural System on Hydrodynamic Variations

• *Change in wave characteristics*: The wave field at the Nhat Le Estuary was analyzed under two dominant monsoon regimes (Northeast and Southwest) for different structural alternatives. Both alternatives effectively reduce wave impacts, especially during the Northeast monsoon when waves are stronger and erosion risks are higher. Under current conditions (PA0), northeast waves directly impact the estuary with heights >1.2 m, causing instability and hindering navigation. In PA1-BW and PA2-BW, waves are refracted and weakened, with PA2-BW more effective in forming a calm-water zone that protects the estuary and stabilizes morphology. During the Southwest monsoon, both options reduce wave penetration, with PA2-BW maintaining wave heights below 0.6 m, protecting the shoreline-particularly the southern coast.

• *Change in flow characteristics*: Simulation results of the seasonal flow field at the Nhat Le estuary for alternatives PA1-BW and PA2-BW indicate that both improve hydrodynamic conditions compared to the current state. However, PA2-BW performs better, providing a stable flow channel, reducing turbulence and nearshore vortices, thereby improving sediment control and limiting erosion. During the Northeast monsoon, its wider jetty spacing decreases flow concentration, eliminates offshore vortices, reduces wave energy on both banks, and creates a calm-water zone that stabilizes morphology and protects navigation. Thus, PA2-BW is considered the more effective and sustainable solution for estuary stabilization.

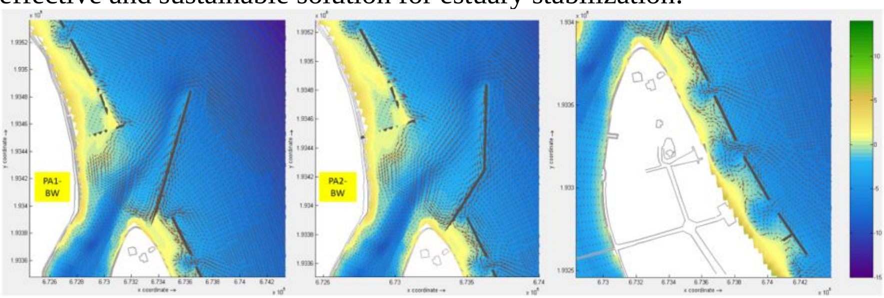


Figure 4.16: Flow distribution field in the project area

4.4 Chapter 4 Summary

Chapter 4 proposed and evaluated several jetty layout alternatives to meet functional and design requirements. The dissertation analyzed the impacts of the spatial configuration of two jetties on flood discharge, establishing a scientific basis for selecting the optimal jetty length and proposing an integrated structural system to stabilize the estuary. The proposed solution effectively achieves river training objectives-ensuring flood safety, navigational efficiency, and morphological stability-validated through long-term morphodynamic simulations.

CONCLUSIONS AND RECOMMENDATIONS

1. Novel Contributions of the Dissertation

(1) Clarified the influence and level of dominance of individual hydrodynamic factors (including waves, local winds within the study area, river discharge, and seasonal sea level variations) on the morphological changes of the Nhat Le Estuary. This was achieved through the application of boundary condition reduction approach in the numerical model.

(2) Developed an approach for establishing a 2DH numerical model capable of long-term simulation (5-10 years) of morphological evolution for the Nhat Le estuary. This approach is based on a combination of statistical analysis (for processing boundary condition data) and advanced numerical modeling (for accelerating morphological computations), thereby overcoming the limitations of computational time typically associated with long-term morphological simulations. The dissertation proposed an appropriate range for the morphological acceleration factor (MorFac, Mf), suggesting Mf values between 5 and 10, combined with a one-year boundary condition dataset, to effectively simulate morphological evolution over a long-term period of 5 to 10 years for the Nhat Le estuary.

(3) Proposed a structural stabilization solution for the Nhat Le Estuary and adjacent coastal areas, specifically option PA2-BW, which includes: A northern jetty, 400 m in length; a southern jetty, 1.100 m in length; a set of three submerged breakwaters and one T-head groyne on the northern coastline; and a set of three submerged breakwaters and one T-head groyne on the southern coastline. This solution helps stabilize the navigation channel at the estuary and minimize the risks of erosion and siltation in the Nhat Le Estuary area. The proposed solution was developed based on an in-depth analysis and evaluation of the spatial arrangement of the structural system to ensure both flood discharge capacity and effective erosion–accretion stabilization, validated through long-term morphological modeling.

2. Main Achievements

The dissertation investigates the morphological evolution and stabilization of the Nhat Le Estuary, emphasizing the dominant hydrodynamic drivers and evaluating engineering solutions using the

Delft3D model. It presents an overview, classification, and analysis of barred estuaries typical in the Central Coast of Vietnam. By synthesizing prior studies, the dissertation identifies key research gaps and establishes a scientific basis for long-term morphological evolution analysis and estuarine stabilization.

Using observational data (1999-2024) and remote sensing images, the dissertation analyzes shoreline and channel evolution of the Nhat Le estuary. Results show strong instability and seasonal migration, with sandbar formation in the wave-river interaction zone causing localized siltation. The dissertation identifies a three-phase morphological evolution cycle consisting of: (1) Wave-dominated state; (2) Combined wave - river flow dominance; and (3) River flow-dominated state.

Using the Delft3D model, the dissertation simulates hydrodynamics, sediment transport, and morphological evolution, clarifying the role of each factor. Wave action, especially during the northeast monsoon, is dominant, shaping longshore currents and sediment movement. River discharge maintains estuary openness, while tides and sea-level variations also affect morphology (Novelty 1). A long-term (5-10 years) morphological model is developed using the morphological acceleration factor (Mf) and boundary condition reduction to improve computational efficiency (Novelty 2). Based on model results, two stabilization options are proposed; option PA2-BW with a 400 m northern jetty, 1100 m southern jetty, six submerged breakwaters, and two T-head groynes proved most effective in stabilizing flow and reducing sedimentation (Novelty 3).

The research outcomes serve as a scientific reference for planning and designing stabilization works for the Nhat Le Estuary and can also be applied to similar estuaries along the central coast of Vietnam.

3. Recommendations for Future Research

• *Limitations of the dissertation:* The study combines boundary condition reduction with Delft3D, improving computational efficiency by 5-10 times. However, a 5-10-year simulation still requires 5-7 days on a Core-i7 PC. The dissertation focuses on long-term analysis, excluding short-term extreme events (floods, storms), climate change, and economic efficiency of engineering solutions have not been evaluated.

• *Directions for further research:* Future study should improve the long-term morphodynamic simulation model for estuaries along the central coast of Vietnam, while optimizing spatial layout and engineering design to enhance technical efficiency and estuarine stability.

LIST OF PUBLISHED PAPERS

[1] Doan Quang Tri, Nguyen Van Nhat, **Vu Dinh Cuong** (2023). Application of deep learning and remote sensing to assess the riverbank change: A case study at Nhat Le river mouth, Viet Nam. Proceedings of the Sixth International Scientific Conference (pages 215-226). The International Conference "Earth and Environmental Sciences, Mining for Digital Transformation, Green Development and Response to Global Change" (GREEN EME 2023, Ho Chi Minh City).

[2] **Vu Dinh Cuong**, Nguyen Thanh Hung, Tran Dinh Hoa, Nguyen Tien Thanh (2024). Shoreline Changes and Sediment Transport along Nhat Le Coast, Vietnam. Engineering, Technology & Applied Science Research. Vol. 14, No. 2, 2024, 13493-13501 (www.etasr.com).

[3] **Vu Dinh Cuong,** Nguyen Thanh Hung, Tran Dinh Hoa (2025). Assessment of the Impacts of Dynamic Factors on the Morphological Changes of the Nhat Le Estuary, Quang Binh Province. Journal of Water Resources Science and Technology, No. 89, April 2025, pp. 2–12.

[4] **Vu Dinh Cuong**, Nguyen Thanh Hung, Tran Dinh Hoa (2025). Morphological changes at Nhat Le estuary under hydro-meteorological influence. J. Hydro-Meteorol. 2025, 23, 60-71; doi:10.36335/VNJHM .2025(23), 60-71.

[5] **Vu Dinh Cuong**, Nguyen Thanh Hung (2025). A Study on the Approach to Long-Term Morphological Simulation of the Nhat Le Estuary, Quang Binh Province. The Builder Journal, No. 399, June 2025, pp. 59–65.

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