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MODELING SEASONAL HYDRODYNAMIC REGIMES AND THEIR ROLE IN SHAPING MEGA CUSPS: INSIGHTS FROM MY KHE BEACH, VIETNAM

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Abstract

This study examines seasonal hydrodynamics shaping coastal morphology at My Khe Beach, Vietnam, with emphasis on mega cusp formation and evolution. A calibrated Delft3D model simulated wave fields, nearshore circulation, and processes using satellite, AUV, bathymetric, tidal, wave, and current data from field campaigns conducted in January and May 2024. The simulations reproduce the seasonal variability in coastal dynamics with reasonable accuracy. During the northeast monsoon, ENE and NE waves with significant heights (Hs) of 1.5–2.0 m generated strong nearshore currents that intensified beach erosion and promoted mega cusp formation. In contrast, during the southwest monsoon, ESE and SE waves with Hs around 1.0 m and oblique incidence angles reduced nearshore flow velocities ($V < 0.2$ m/s), mitigating erosional processes and contributing to beach profile stabilization. Results emphasize seasonal wave forcing as a key driver of coastal morphology and present a robust modeling framework to support management in monsoon-influenced regions.

Keywords: coastal erosion, mega cusp, hydrodynamic modeling, monsoon waves, Delft3D

1. Introduction

Coastal erosion and shoreline instability pose significant challenges worldwide, exacerbated by global climate change, socio-economic development, and increasing tourism pressures. Understanding and integrating coastal morphodynamics - the dynamic interaction between waves, currents, sediment transport, and shoreline evolution - is essential for sustainable coastal planning and management. As climate change accelerates sea-level rise and intensifies storm events, many coastal systems become increasingly vulnerable to erosion, flooding, and habitat loss (Clark, 1997; Martínez et al., 2011). This vulnerability is particularly critical in rapidly developing coastal regions, where infrastructure and livelihoods are directly exposed to shoreline instability. Aligning coastal development with the natural behavior of sedimentary systems can reduce long-term risks and promote sustainable interactions between human and natural systems.

Global climate models predict an increase in the frequency and intensity of extreme coastal events, while concurrent expansion of urbanized coastal zones amplifies both exposure and vulnerability, escalating overall coastal risk (IPCC, 2023; Kulp & Strauss, 2019). Southeast Asia exemplifies this trend, identified as a global hotspot for coastal hazards due to its dense

coastal populations, rapid urban development, and high dependence on marine-based economies (Vila-Concejo et al., 2024; Hue et al., 2020).

Effective coastal adaptation strategies must be tailored to the specific hydrodynamic forcing, sedimentary regimes, and socio-economic contexts of each site. Recent studies emphasize combining hydrodynamic modeling, morphological forecasting, and stakeholder engagement to identify optimal trade-offs between protection, conservation, and development (Morales, 2022; Chowdhury et al., 2023). Such site-specific approaches are essential for designing sustainable interventions that align with both natural coastal dynamics and long-term human interests.

Mega cusp beaches are prominent rhythmic shoreline features characterized by large-scale embayments alternating with protruding cusp horns, typically spaced hundreds of meters apart (e.g., Thornton et al., 2007; Short & Masselink, 1992). These features are formed through the interaction of waves and nearshore currents, often associated with standing edge-wave patterns or rip current cells. Unlike depositional features such as spits or tombolos, mega cusp beaches accentuate shoreline rhythmicity through their embayment-cusp system and are highly sensitive to variations in hydrodynamic forcing. Their well-defined cusp patterns play a critical role in sediment redistribution, with erosion typically concentrated in the embayments and deposition occurring at the cusp tips.

The formation and evolution of mega cusp beaches are shaped by both natural processes and human activities. In monsoon-dominated regions such as Southeast Asia, seasonal wave regimes exert a strong control on coastal morphodynamics. During the northeast monsoon, energetic waves and enhanced rip-current circulation intensify cross-shore sediment transport, which accentuates and maintains cusp embayments. In contrast, the calmer southwest monsoon favours onshore sediment transport and partial infilling of embayments, smoothing the cusp morphology (Thanh et al., 2018). These alternating conditions create a cyclical pattern of erosion and recovery that is critical for understanding shoreline stability.

The dominant hydrodynamic regime **(**whether wave-dominated, tide-dominated, or mixed) also shapes the morphodynamic response of the coast. Wave-dominated systems are typically characterized by strong longshore currents and bar-trough morphologies, while tide-dominated systems exhibit broader intertidal zones and more uniform sediment transport patterns.

A key parameter in sediment transport and morphological change is bed shear stress, which quantifies the force exerted by fluid flow on the seabed (Nielsen, 1992). When this stress exceeds a critical threshold, sediment is mobilized, leading to erosion or redistribution. Seasonal variations in wave height and direction significantly influence bed shear stress, particularly during storm events or monsoonal transitions.

Longshore currents and rip currents are also fundamental components of nearshore circulation, each playing a critical role in sediment transport and the development of cuspate shoreline features (Wright & Short, 1984). Longshore currents, generated by waves approaching the coast at an oblique angle, redistribute sediment parallel to the shoreline and drive progressive shoreline change. In contrast, rip currents - narrow, seaward-directed flows often concentrated in low points or embayments - export sediment offshore, deepening embayments and influencing cusp spacing (Guza & Inman, 1975; Castelle et al., 2016). The interaction between these two current systems and the pre-existing beach morphology establishes feedback mechanisms that can either stabilize rhythmic shoreline features under steady forcing or destabilize them during storms and changing wave regimes.

Recent advances in sediment tracing, particularly the application of radionuclide mapping, have expanded the capacity to identify deposition and erosion zones along dynamic coastlines. By capturing fine-scale spatial patterns of sediment redistribution, this method provides a robust tool for diagnosing coastal processes. Its utility is most evident in environments with contrasting wave exposure, where sheltered and exposed zones can be clearly distinguished (Tsabaris et al., 2025).

My Khe Beach, on the eastern coast of Da Nang, is a major tourist destination and key regional asset, yet it is highly dynamic due to its moderate tidal range (~1.2 m) and strong seasonal wave forcing. Situated between the Cua Dai estuary and the Son Tra Peninsula, it exhibits mixed tidal and wave-driven processes that generate distinctive mega cusps—shoreline features with 100–300 m spacing and up to 50 m radii—forming under northeast monsoon conditions and dissipating during the calmer southwest monsoon. Despite its socio-economic importance, the beach has suffered recurrent erosion, notably in December 2017, with satellite imagery showing scouring concentrated in cusp embayments. While previous studies (Viet et al., 2015; Tanaka et al., 2016, 2017; Tinh et al., 2018) underscored the need for detailed analysis, site-specific investigations of the hydrodynamic drivers remain limited. This study addresses that gap by numerically simulating seasonal regimes governing the formation and evolution of mega cusps at My Khe Beach (Figure 1).

Remote sensing data analysis has indicated that the formation of large mega cusps is one of the primary factors driving erosion at My Khe Beach (Viet et al., 2018). Satellite imagery analysis shows that the alongshore spacing (λ) of these features ranges from 100 to 300 meters, with cusp radii (h) reaching up to approximately 50 meters, clearly reflecting the influence of wave dynamics on beach morphology in this area (Figure 1). These cuspate formations result from the complex interaction between wave action and coastal currents, where prolonged high-energy wave conditions alter sediment transport dynamics and coastal topography, with erosion concentrated in the embayments where sediment removal is most intense (Thornton et al. 2007).

Understanding coupled hydrodynamic and sedimentary processes is critical for studying mega cusps, which serve as natural laboratories for assessing coastal vulnerability and resilience. On rapidly urbanizing shorelines such as Da Nang, where infrastructure and tourism are highly exposed, these insights directly inform adaptive coastal management. Accounting for seasonal seabed dynamics is essential, as process-based approaches offer greater resilience to anthropogenic pressures and climate change. Site-specific approaches are particularly important to ensure sustainable interventions that align with coastal morphodynamics, as interactions between current systems and beach morphology can either stabilize or destabilize rhythmic shoreline features under varying wave regimes and storm events.

The objective of this study is to simulate the hydrodynamic regimes and morphological changes in the My Khe beach area; the collection of input data is of paramount importance to ensure the accuracy and feasibility of the modeling process. For future sediment transport study, this study presents for the first time a numerical model to simulate hydrodynamic regime on My Khe beach to describe the asymmetric gain and loss of sediment, characterizes the long-term irreversible tendency to erosion (Figure 1). This will serve in future to validate a morphodynamic beach model and further design adaptation solution to minimize climate effects on this region. This study focuses on the detailed simulation and analysis of hydrodynamic factors to determine the relationship between wave dynamics, nearshore circulation, and the occurrence of mega cusps erosion along the My Khe coastline.

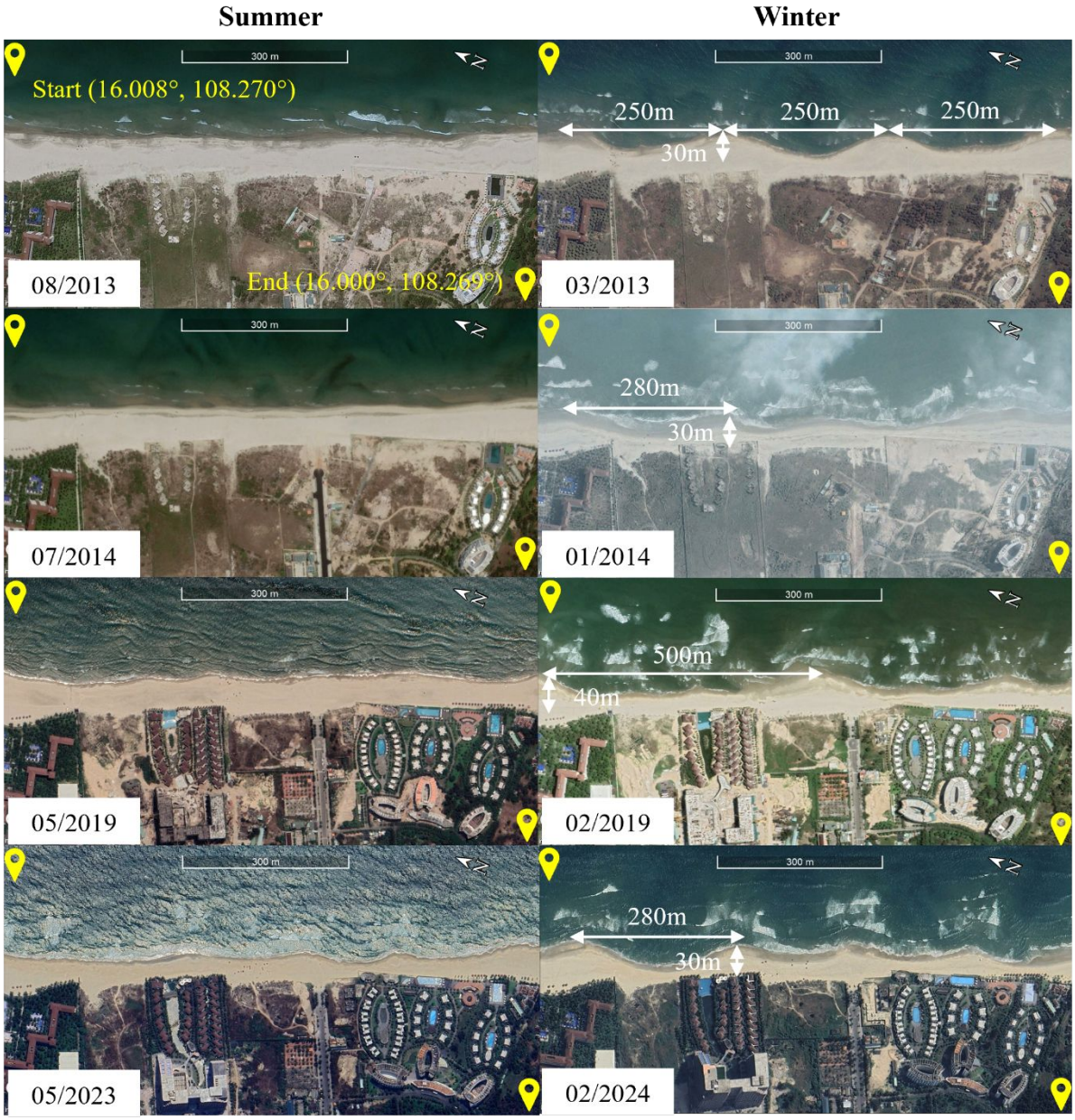

Fig. 1. The coastal morphology of My Khe Beach with the presence of a mega beach cusp (in winter) and its absence (in summer) with start/end GPS points. (Figure was created using Google Maps, version 2025 and assembled from the following data source: Research project 2022-2025 titled "*Development of a Toolset for Assessing and Forecasting Morphological Changes and Proposing Stabilization Solutions for Beaches in the Central Coastal Region of Vietnam*".)

The structure of the paper is organized as follows: In Section 2, we introduce the study area and outline the methodology, including data collection and hydrodynamic modeling approaches. Section 3 presents the results of the numerical simulations, focusing on wave dynamics, nearshore currents, and bed shear stress under seasonal monsoon conditions. Finally, Section 4 provides a discussion of the findings, highlighting the influence of monsoonal variability on coastal morphodynamics and addressing the limitations of the study.

2. Site and methodology

2.1 Study site: My Khe beach

My Khe Beach, located on the eastern coast of Da Nang, is renowned for its white sandy shores, clear blue waters, and mild climate. With its favorable geographical position -bordered by the Cua Dai estuary to the south and the Son Tra Peninsula to the north - My Khe plays a vital role in the development of the Central Region's marine economy, particularly in tourism and services. However, over the past decade, the beach has been facing severe erosion, causing significant damage to coastal infrastructure. This issue has been observed since 2017, especially in the area stretching from the My Khe drainage outlet to the Premier Village resort, and most recently in January 2025, when erosion at the My Khe bathing area led to the destruction of several structures (Figure 2). Satellite imagery shows mega beach cusps with 100–300 m spacing and ~50 m curvature radii, where erosion concentrates in embayments. MBES-derived DEM differencing over 5 km (January 2024–2025) reveals a net nearshore sediment loss of ~1.17 × 10^6 m³. Bed lowering dominates within 200–250 m of the shoreline, with partial redistribution 300–450 m offshore, while morphodynamic adjustments remain mainly within the inner 500 m and sediment displacement extends up to ~400 m offshore.

Fig. 2. My Khe beach, Da Nang (Vietnam) and Cua Dai estuary between Son Tra Peninsula and Dung Quat headland. Waves data at Point P at 100m depth, Station A (16,048°; 108.256°) at 12m depth and B (16.051°; 108.268°) at 6m depth for waves and currents measured by AWAC equipment (Figure was created using Google Maps, version 2025 and assembled from the following data source: Research project 2022-2025 titled "*Development of a Toolset for Assessing and Forecasting Morphological Changes and Proposing Stabilization Solutions for Beaches in the Central Coastal Region of Vietnam*".)

The beach frequently exhibits mega cusps erosion, a geomorphological feature shaped by the interaction of waves and nearshore currents, where the shoreline takes on a sawtooth-like pattern. During periods of strong wave activity, sediments are transported offshore, forming submerged sandbars, while weaker wave conditions promote sediment deposition and the development of large mega cusps features, particularly during the northeast monsoon season. Erosion primarily occurs in the embayments between the cusps, where sediment is most intensely scoured (Việt et al., 2018). In contrast, during the southwest monsoon season, when wave energy is lower, these cuspate features gradually flatten and reshape, contributing to shoreline stabilization.

Shoreline positions were extracted using a multi-platform monitoring framework that integrates satellite remote sensing and UAV photogrammetry. Multi-decadal shoreline dynamics were reconstructed from the Landsat series (5 TM, 7 ETM+, 8/9 OLI/TIRS; 30 m spatial resolution, 16-day revisit) for the period January 1990–December 2024, and from Sentinel-2 MSI for the period June 2015– December 2024 (10–20 m spatial resolution, 5-day revisit) for the period 1990–2024. These satellite datasets, processed with the CoastSat toolbox and corrected for tidal stage, provided a consistent synoptic record for quantifying long-term erosion and accretion patterns along the Da Nang coast. The extracted shorelines are subject to inherent uncertainties from sensor resolution and geolocation, cloud/sun-glint and wave foam, and CoastSat's automated classification.

To capture finer-scale variability, UAV surveys were conducted between 2022 and 2024 at My Khe Beach. The surveys produced orthomosaics and high-resolution digital elevation models with ground sampling distances of 2–5 cm, which were validated against RTK-GNSS ground control points and in-situ beach profiles. Together, the integration of these observation systems established a nested, multi-scale dataset: satellites for multi-decadal trends and UAVs for seasonal to interannual dynamics

2.2 Data Collection and Input Parameters

To simulate the hydrodynamic regimes and morphological changes in the My Khe beach area, the collection of input data is of paramount importance to ensure the accuracy and feasibility of the modeling process. The dataset used in this study was obtained from the research project 2022-2025 titled "*Development of a Toolset for Assessing and Forecasting Morphological Changes and Proposing Stabilization Solutions for Beaches in the Central Coastal Region of Vietnam*".

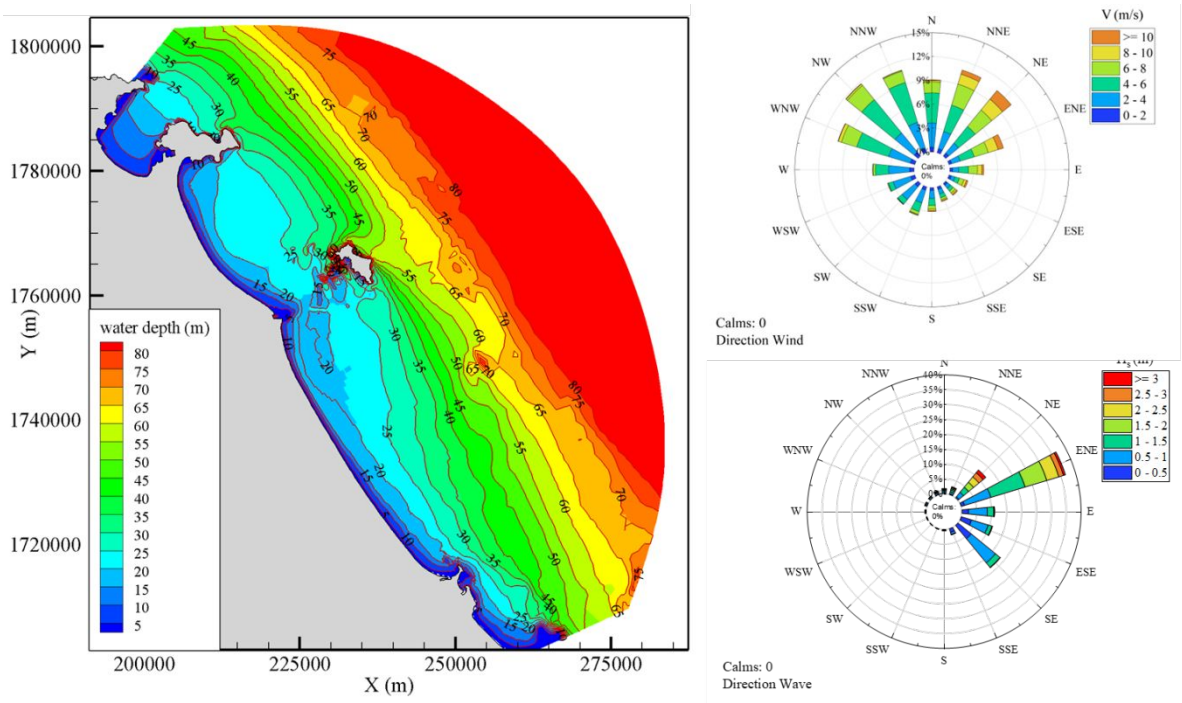

Fig 3. Site data and offshore forcing statistics for My Khe Beach (Da Nang, Vietnam): bathymetry (left); wind rose from NCEP–NOAA 10-m winds (U_{10},V_{10}) at point P (top-right);

wave rose from WAVEWATCH III based on Station A and B (bottom-right).

2.2.1. Bathymetry data

The dataset comprises several topographic and bathymetric mapping products to characterize both terrestrial and underwater zones of the My Khe beach area and its broader coastal region. A detailed topographic survey map of the My Khe beach terrestrial zone was prepared at a fine scale of 1:500, with contour intervals of 0.5 meters. This high-resolution map provides precise elevation data essential for understanding landform features and coastal slope gradients. For the adjacent submerged zone, a bathymetric map was produced at a scale of 1:2000, featuring 1.0-meter contour intervals to capture the underwater terrain with adequate detail for coastal process modeling. These smaller-scale maps allow for detailed analysis of shoreline changes and nearshore morphology.

To extend the spatial context beyond the immediate beach zone, a broader regional coastal bathymetric map covering the coastline from Quang Nam to Quang Binh provinces was also incorporated. This map, originally surveyed by the U.S. Navy in 1970, is at a scale of 1:50,000 with 20-meter contour intervals. Although coarser in resolution, it offers critical information on offshore bathymetry and seabed gradients influential to sediment transport and wave dynamics on a regional scale. Additionally, global bathymetric grid data from the General Bathymetric Chart of the Oceans (GEBCO) were utilized to supplement regional assessments and provide a comprehensive overview of underwater topography extending offshore (Figure 3).

Together, these multi-scale datasets enable integration from fine local terrain and seabed features to broader regional slopes and depths, facilitating a detailed understanding of coastal and nearshore morphodynamics at My Khe and its surrounding coastal waters.

2.2.2. Hydrodynamic data

Tidal boundary conditions for this study were extracted from the TPXO7.0 global tidal model (Egbert and Erofeeva, 2002). The amplitudes of the principal tidal harmonic constituents (K1, O1, M2, and S2) were determined to be 0.17 m, 0.11 m, 0.19 m, and 0.07 m respectively. Using these harmonic amplitudes, yielding a tidal form factor $F=1.077$ (Pugh, 2004; Van Maren et Gerritsen, 2012). This indicates a mixed tidal regime at My Khe Beach. While the semi-diurnal M2 component exhibits the largest amplitude at 0.19 m, the diurnal constituents K1 and O1, with amplitudes of 0.17 m and 0.11 m respectively, exert significant influence on the overall tidal dynamics. According to tidal classification criteria, a form factor F value between 0.5 and 1.0 typically characterizes a mixed tide with a dominance of semi-diurnal components. However, at My Khe Beach, with an F factor slightly above this range at 1.077, the tidal regime is best described as mixed with a prevailing diurnal influence. This nuanced tidal character is critically important for understanding and predicting tidal fluctuations, as it affects sediment transport, coastal circulation patterns, and the morphology of coastal features such as mega cusps. Accurately characterizing the tidal regime supports improved modeling of coastal processes and informs management efforts aiming to mitigate environmental and anthropogenic impacts in the region.

Wave climate data from 2000 to 2023 were extracted from the third-generation reanalysis wave model WAVEWATCH III, developed by NOAA. Wind forcing was taken from the NCEP–NOAA reanalysis as standard 10-m winds (U_{10}, V_{10}) over the sea surface (hourly; 0.2° × 0.2°; 2000–2024). Wind and wave time series were extracted at an offshore point P (16.5°N, 108.5°E), approximately 100 km seaward of My Khe Beach (Figure 2), to derive the wind/wave

rose statistics (Figure 3) and to define offshore forcing. In addition, wave climate data were measured at points A, B (Figure 2) using AWAC from 2020 to 2025. Finally, for the present study aiming to develop and validate the coastal model for future sediment transport assessment, the two recent field survey data were conducted in January and May 2024. Measurements at stations A and B included water levels, wave parameters, and current velocities, with survey periods spanning from January 16–23, 2024 (campaign 1, monsoon winter or NorthEastern) and May 15–22, 2024 (campaign 2, monsoon summer SouthEastern). The locations of these stations are illustrated in Figure 2.

Nearshore wave induced current are measured at point A, B using velocimetry sensor (Nortek) during the same period January 16-23 and May 15-22, 2024. From measurements, it is observed an intense longshore current from North to South during the winter (or ENE) monsoon and a moderate current from south to North during the summer (or ESE) monsoon.

2.2.3. Shoreline data

The shoreline dataset at My Khe Beach provides an integrated record of morphological variability spanning seasonal to interannual timescales (Figs. 4–5). Rather than exhibiting a uniform trend, the shoreline demonstrates cyclic erosion and recovery patterns related to cusps dynamics under alternating monsoon regimes. Significant shoreline retreat occurs within embayment zones during the northeast monsoon (e.g., January 2017, 2024), whereas calmer conditions in the summer months promote partial accretion and restoration of cusp morphology.

High-resolution bathymetric surveys conducted between 2024 and 2025 complement these observations by revealing nearshore morphological features such as rip channels, submerged bars, and offshore cusp extensions. These seabed structures exert strong control over sediment circulation and transport pathways. The spatial correspondence between seabed morphology and erosion hotspots underscores the close coupling between wave climate, cross-shore sediment exchanges, and shoreline adjustment processes.

Collectively, this comprehensive dataset establishes a robust empirical baseline for linking hydrodynamic forcing to morphodynamic responses, offering essential insights for future sediment transport modeling and comparative studies of monsoon-dominated coastal systems.

2.3 Hydrodynamic model

The study on hydrodynamic regimes and sediment transport processes at My Khe Beach was conducted using the Delft3D modeling suite developed by Deltares to provide insight into the physical processes explaining the cyclicity in the formation of megacusp and their smoothening during the ENE (winter) and ESE (summer) monsoon respectively.

For the coupling between tides and waves, two main modules are selected for computation on a curvilinear orthogonal grid. On the one hand, Delft3D-Flow module solves the so-called shallow water equation (SWE) assuming hydrostatic pressure and depth-integrated velocities. On the other hand, Delft3D-Wave is used for wave propagation and interaction (Lesser et al., 2004). The coupling between these two modules through radiation stresses enables the analysis of wave–current interactions and gives access to the bed shear stresses which are crucial parameter for future sediment transport study but are very difficult to assess in field conditions.

Figure 4 presents the extend of computational domain which is subdivided in two subdomains:
(i) The oceanic domain covers a zone of 120 x 50 km^2 to include the Son Tra Peninsula at the northern limit and the Dung Quat Headland at the southern limit. The Wave boundary conditions were derived from NOAA's WAVEWATCH III model at offshore point P.
(ii) The coastal domain covers a zone of 50 x 25 km^2 centered to the Cua Dai estuary and Cu Lao Cham Island. The Tide boundary conditions were derived from the TPXO7.0 global tidal

model.

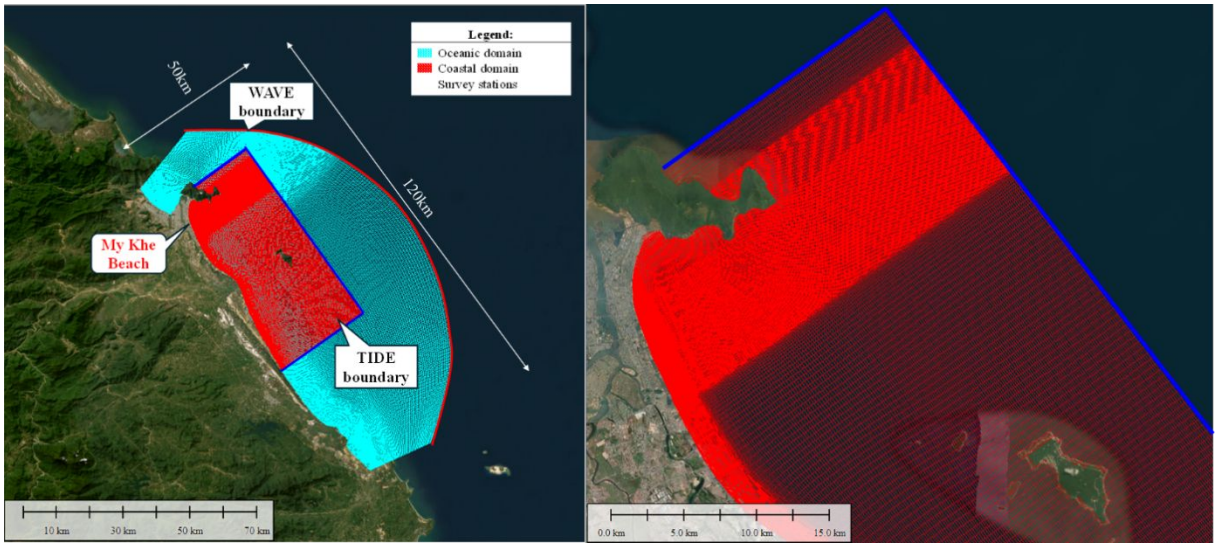

Fig 4. Computational domains and open boundaries : (1) oceanic domain for wave propagation with the offshore wave boundary (Delft3D-WAVE) forced by WAVEWATCH III at point P; and (2) coastal domain for tide-driven circulation with open-boundary water levels (Delft3D - FLOW) prescribed from TPXO7.0 tidal constituents. (Figure was created using Google Maps, version 2025 and assembled from the following data source: Research project 2022-2025 titled "*Development of a Toolset for Assessing and Forecasting Morphological Changes and Proposing Stabilization Solutions for Beaches in the Central Coastal Region of Vietnam*".)

For Delft3D-FLOW, tidal water levels are implemented as harmonic forcing (data extracted from TPXO7.0 tidal constituents), and vary in time and along the open boundaries, i.e., not constant along the boundary line. For Delft3D-WAVE, the offshore wave boundary is uniform along the boundary, using a time series (data extracted from WAVEWATCH III at point P) for calibration/validation and stationary sea states for scenarios.

2.4 Model Calibration and Validation

The selection of model parameters is a crucial and complex process, carried out through multiple iterations of adjustment and testing to achieve accurate simulation results. These parameters include the model domain, grid size, time step, and physical parameters. Among these, determining the model domain and grid size is particularly important, especially in the nearshore region, where wave and flow dynamics vary significantly.

Table 1. Key model parameters for Flow and Wave Modules

Parameters	**Flow Model**	**Parameters**	**Wave Model**
Manning	0.026	gamma	0.73
Eddy viscosity	1 m^2/s	alpha	1
Dryflyc	0.05 m	Bottom friction	0.067 m^2/s^3
		Min. depth	0.05 m

This area is influenced by a variety of hydrodynamic and topographic factors, which require careful consideration of the model's extent and grid resolution. To accurately simulate processes in this region, the computational grid is set with 320 grid cells in the M direction, 500 grid cells in the N direction, and a minimum grid size of 30 m x 30 m for the coarse grid. For more detailed simulations, the fine grid is adjusted to 650 grid cells in the M direction, 500 grid cells

in the N direction, with a minimum grid size of 10 m x 10 m, ensuring higher resolution, especially in the shallow water areas and the time step is adjusted to 1 minute. These optimal resolution was based on a space–time convergence analysis, conducted by progressively refining the grid resolution from 50 m to 5 m and reducing the computational time step from 5 min to 10 s. Based on these tests, a nested-grid configuration with a final time step of $\Delta t = 1$ min was adopted as an optimal compromise between numerical stability and computational efficiency. The selected setup satisfies the CFL stability criterion throughout the domain. Details of the convergence strategy and its application are consistent with methodologies reported in Dien et al. (2019).

For the Delft3D-wave model, the default value of JONSWAP parameters were applied (Battjes and Janssen's model). The only adjustment concerned the wave rose discretization, using 36 wave directions, each divided into 100 segments, with frequencies ranging from 0.05 Hz to 1 Hz, and distributed over 24 frequency bands. For the Delft3D-Flow model, the only three parameters (Manning bottom friction, eddy viscosity and wet/dry threshold) were adjusted through calibration and verification. We consider here a constant eddy viscosity model. Table 1 summarizes the parameter values obtained from the validation procedure.

In this study, the model was calibrated and validated using field data collected in January and May 2024 at Stations A and B (Figure 2), located offshore of the My Khe Beach area. Water level, wave, and current velocity measurements from January 2024 were used for calibration, with parameters adjusted to minimize the Root Mean Square Error (RMSE) and Mean Error (ME), while maximizing the Nash–Sutcliffe Efficiency (NSE) coefficient (Williams & Esteves, 2017). Model accuracy was further verified through comparison with May 2024 observations. The calibration and verification processes ensured that simulated wave and flow dynamic are closely reproduced observed conditions, thereby improving confidence in the model's ability to represent natural processes within the study area.

$$RMSE = \sqrt{\frac{1}{N}\sum_{1}^{N}(S_i - O_i)^2} \quad ME = \frac{1}{N}\sum_{1}^{N}\left|O_i - S_i\right| \quad NSE = 1 - \frac{\sum_{i=1}^{Ni}(S_i - O_i)^2}{\sum_{i=1}^{Ni}(O_i - \overline{O_i})^2}$$

where Oi stands for the observed value, Si the simulated value, N the number of data points, and $\overline{O}$ the mean of the observed data series.

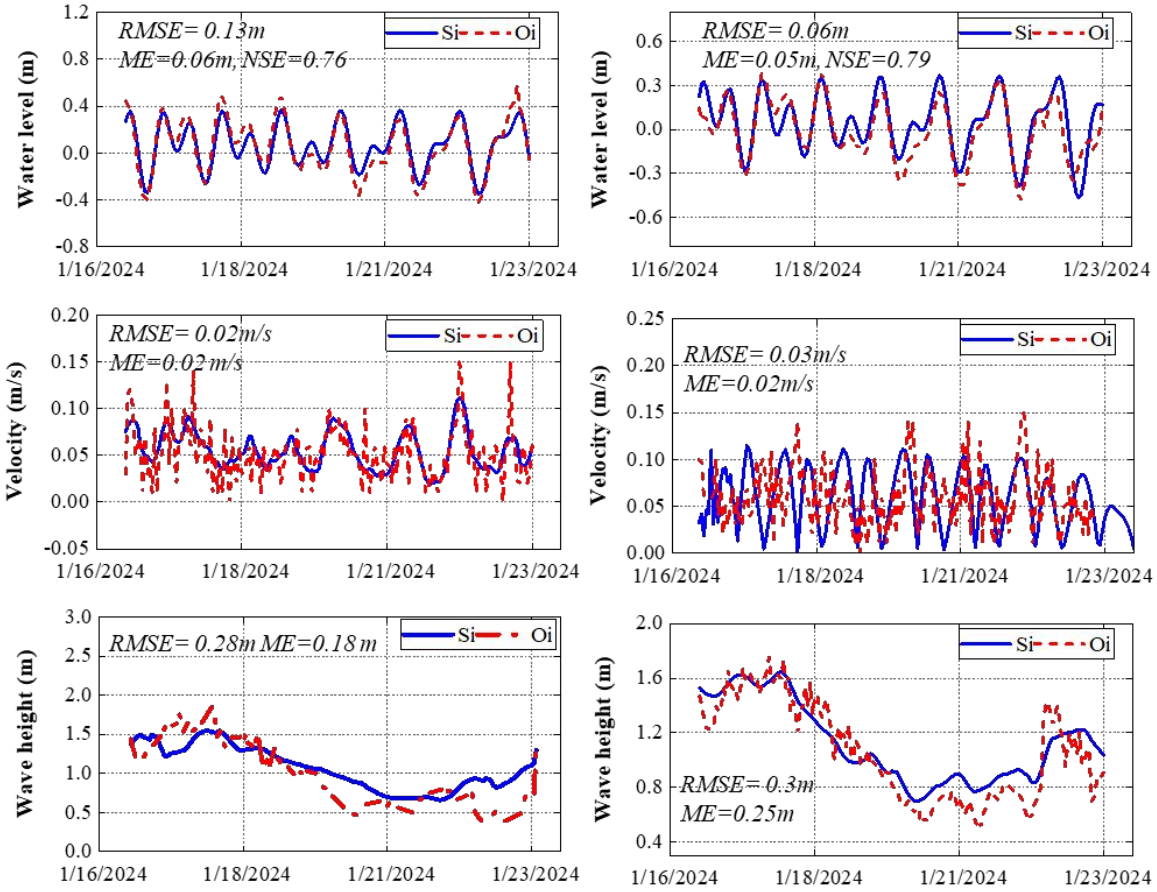

Fig 5. Results of Calibration on water level, current, and wave parameters at Station A (left) and Station B (right) during the first (January 2024) survey campaign

During calibration (Figure 5), water levels were reproduced with RMSE of 0.05–0.08 m and NSE of 0.76–0.79, while current velocity errors remained low (RMSE of 0.06–0.12 m/s). Significant wave height (*Hs*) showed RMSE of approximately 0.28–0.30 m under higher-energy winter conditions.

During verification against the May 2024 independent dataset (Figure 6), comparison yielded stable or similar performance, with water-level RMSE of 0.05–0.06 m and NSE of 0.86–0.88, and *Hs* RMSE of approximately 0.20 m.

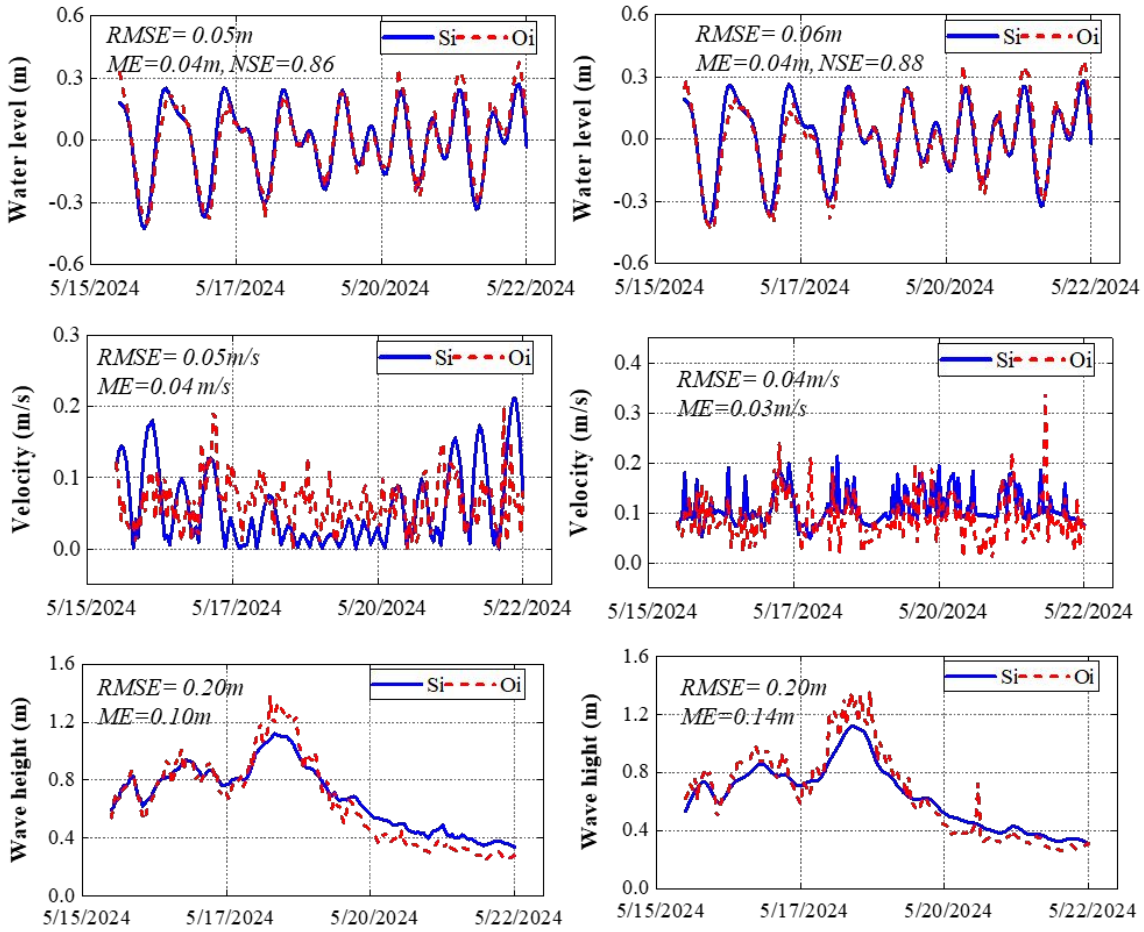

Fig 6. Results of Verification on water level, current, and wave parameters at Station A (left) and Station B (right) during the second (May 2024) survey campaign

It is also noted that wave and current intensities during the calibration period were higher than those observed during the verification period, which partly explains the slight differences in error magnitude. Also, the discrepancies between Observed (Oi) and simulated (Si) values for the both, calibration and verification cases, may be attributed to (i) measurement uncertainty and short-lived variability in the surf zone and (ii) nearshore modelling limitations, including sensitivity to offshore forcing, local bathymetry, and SWAN surf-zone parameterizations (breaking/whitecapping/bottom friction), which particularly affect peak Hs (see Section 4.2). Overall, the comparable verification skill without retuning confirms that the selected configuration is physically consistent and not driven by case-specific tuning, providing a reliable basis for subsequent scenario simulations and morphodynamic analyses.

3. Hydrodynamic Simulation of the My Khe Coastal Area

3.1 Simulation Scenarios

A detailed analysis of multi-year wave data from 2000 to 2023 for the Da Nang coastal region provides a robust characterization of the nearshore wave climate relevant to the My Khe shoreline. For regime interpretation and scenario design, the long-term record was partitioned into monsoon-controlled seasons and dominant incident directional sectors consistent with the discrete model forcing directions (Table 2): winter NE (Dir = 45°) and ENE (Dir = 60°), and summer ESE (Dir = 135°) and SE (Dir = 150°). Seasonal representative significant wave heights

(Hs) were defined using the central tendency (mean/median band) of each seasonal Hs distribution, yielding 0.8–0.9 m for summer and 2.1–2.2 m for winter; these narrow ranges reflect interannual variability while remaining representative of typical seasonal (background) forcing used for regime characterization.

The coastal environment is mainly characterized by a mixed tidal regime, predominantly semi-diurnal, having an average tidal range of about 1.2 meters. Such tidal characteristics are consistent with regional observations reported in prior studies (e.g., Tran et al., 2015). The dynamic interaction between wave and tidal processes at My Khe beach is illustrated in Figure 8, highlighting the temporal variability and relative contributions of these hydrodynamic forces.

According to the coastal classification scheme based on wave–tide interactions developed by Hayes (1979), coastal environments can be categorized into tide-dominated, wave-dominated, or mixed regimes depending on the relative energy contributions of waves and tides. Applying this framework to the My Khe beach area indicates a predominantly wave-dominated regime, especially during monsoonal seasons (Figure 7). This wave dominance is more particularly pronounced during the winter northeast (NE) and east-northeast (ENE) monsoon periods, when prevailing winds and swell conditions intensify wave energy impacting the shoreline (Nguyen & Pham, 2020). Such seasonal variability in hydrodynamic forcing has significant implications for coastal sediment transport, shoreline morphology, and erosion patterns in the region.

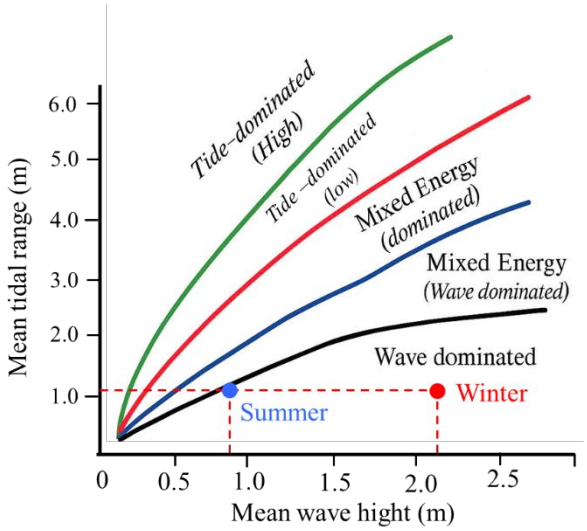

Fig 7. Seasonal representative H_s values (summer: 0.8–0.9 m; winter: 2.1–2.2 m) from the 2000–2023 record by monsoon-season and directional-sector partitioning and taking the central tendency of each seasonal H_s distribution; ranges indicate interannual variability.

Based on the multi-year deep-water (offshore) wave statistics compiled for 2000–2023 for the My Khe coastal area, the previously validated numerical hydrodynamic model was applied to investigate a range of representative climatic scenarios. The two tidal simulation windows selected for winter and summer correspond to the periods used to validate the model's season-specific tidal parameters, based on observed water-level records collected during the January (winter) and May (summer) field campaigns. Wave scenarios (Table 2) were designed to span representative seasonal sea states within the dominant directional sectors adopted in the model.

The multi-year deep-water wave statistics (2000–2023) indicate a pronounced directional concentration within the eastern sector, with ENE dominating (36.89%), followed by SE (18.17%), NE (12.17%), E (10.88%), and ESE (10.87%), whereas all remaining directions

occur much less frequently (<3% each). In terms of wave-height distribution, the most common conditions are Hs = 0.51–1.0 m (37.73%) and Hs = 1.01–2.0 m (32.63%), followed by Hs < 0.5 m (16.12%) and Hs = 2.01–3.0 m (11.22%); wave heights exceeding 3.0 m are rare (3.01–4.0 m: 2.05%; 4.01–15 m: 0.25%).

A calm-condition case (KB13) was included as a reference baseline. This calm case provides a "tide-only" benchmark to isolate and quantify wave-driven contributions (e.g., wave-induced setup and currents) relative to tidally driven hydrodynamics. The complete set of scenarios used for subsequent analyses is summarized in Table 2, providing an overview of the hydrodynamic boundary conditions applied in the simulations.

Table 2. Hydrodynamic simulation scenarios for the Da Nang coastal area

Scénarios	Tidal simulation period	Period of influence	Parameters	Frequency (%)
KB1	16/01/2024–23/01/2024	NE-sector waves (winter)	Hs=2,5 m; Tp=8,0 s; Dir=45°	4,13
KB2	16/01/2024–23/01/2024	NE-sector waves (winter)	Hs =2.0 m; Tp = 8.0 s; Dir = 45°	4,40
KB3	16/01/2024–23/01/2024	NE-sector waves (winter)	Hs=1,0 m; Tp=6,0 s; Dir=45°	1,91
KB4	16/01/2024–23/01/2024	ENE-sector waves (winter)	Hs=2,0 m; Tp=6,0 s; Dir=60°	19,84
KB5	16/01/2024–23/01/2024	ENE-sector waves (winter)	Hs=2,5 m; Tp=8,0 s; Dir=60°	5,87
KB6	16/01/2024–23/01/2024	ENE-sector waves (winter)	Hs=1,0 m; Tp=6,0 s; Dir=60°	9,30
KB7	16/01/2024–23/01/2024	E-sector waves (winter)	Hs=1,5 m; Tp=6,0 s; Dir=90°	2,29
KB8	16/01/2024–23/01/2024	E-sector waves (winter)	Hs=1,0 m; Tp=6,0 s; Dir=90°	6,28
KB9	15/05/2024–21/05/2024	ESE-sector waves (summer)	Hs=1,5 m; Tp=6,0 s; Dir=135°	1,30
KB10	15/05/2024–21/05/2024	ESE-sector waves (summer)	Hs=1,0 m; Tp=6,0 s; Dir=135°	5,82
KB11	15/05/2024–21/05/2024	SE-sector waves (summer)	Hs=1,5 m; Tp=6,0 s; Dir=150°	1,96
KB12	15/05/2024–21/05/2024	SE-sector waves (summer)	Hs=1,0 m; Tp=6,0 s; Dir=150°	10,33
KB13	15/05/2024–21/05/2024	Calm (tide-only baseline)	Calm conditions	16,12
Other conditions	—	—	Remaining Dir–Hs classes	**10,45**

3.2 Nearshore Wave Characteristics

Northeast Monsoon Period

Figure 8 (a,b) presents the simulated wave field in the My Khe coastal zone associated with the northeast (NE) monsoon season. The numerical wave model captures the spatial variability of wave propagation induced by the complex coastal morphology, particularly the strong curvature of the shoreline near the Son Tra Peninsula and the Cu Lao Cham Island. This morphological system, the peninsula and the island, explains the convergence effect of wave rays during NE monsoon, or the focalization of wave energy hitting the My Khe beach. The

alongshore wave-induced currents are intensified and increase the capacity for sediment mobilization and redistribution along the shore.

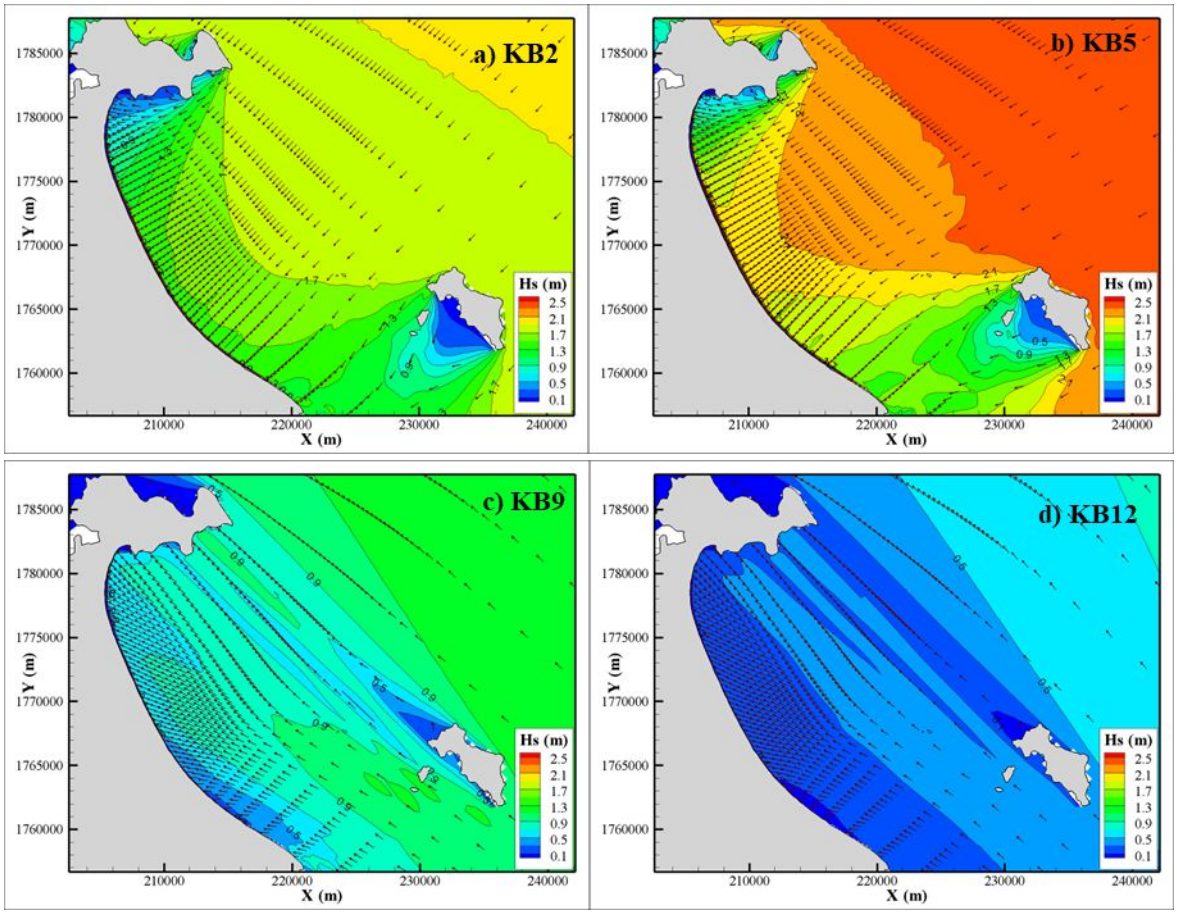

Fig 8. Simulated wave fields in the My Khe beach area at selected times illustrating the characteristic spatial patterns and propagation directions under (a, b) northeast monsoon wave conditions (scenarios KB5 and KB2, respectively) and (c, d) southern monsoon wave conditions (scenarios KB9 and KB12, respectively).

The convergence effect of waves together with the presence of sheltered zones behind peninsula and island amplifies sediment transport gradients, which in turn exacerbates erosion phenomena within embayed coastal sectors (Tsabaris et al. (2025)). In this case, field observations indicate that these processes conduct the formation and amplification of megacusp (Tanaka et al. 2016, 2017). The simulated wave field also indicates that offshore waves approaching the Son Tra Peninsula under NE and east-northeast (ENE) wave scenarios consistently refract and propagate shoreward, reinforcing the wave energy flux directed toward the coastline. The wave directional pattern generated by the coastal geometry during the NE or ENE monsoon is the dominant explanation for the spatial patterns with mega cusps observed in the region.

These findings align with established coastal morphodynamic principles, whereby wave convergence zones are hotspots for intensified hydrodynamic forcing and sediment redistribution (Komar, 1998; Masselink & Hughes, 2003). Understanding these interactions is essential for predicting shoreline evolution and informing coastal management strategies aimed at mitigating erosion risks along the My Khe coast.

Southwest Monsoon Period

Contrary to the higher-energy wave regime associated with the winter northeast monsoon, the summer monsoon wave climate coming from the southeast sector presents significantly lower energy levels along the My Khe shoreline (Figure 8 c,d). Specifically, waves arriving from the east-southeast (ESE) and south (S) directions are strongly attenuated due to the sheltering effect of Island. The latter acts as a natural barrier, protecting the coastline by reducing the nearshore significant wave heights below 0.5 meters.

These relatively calm swell conditions promote sediment deposition, leading to net accretion which is observed by beach widening within embayed areas. This sediment accumulation tends to diminish the amplitude of mega cusps features and contributes to the overall stabilization of the My Khe coastal zone. Such seasonal variability in wave energy and sediment dynamics highlights the critical role of local geomorphological features in modulating coastal processes (e.g., Wright & Short, 1984; Masselink & Hughes, 2003).

3.3 Nearshore Current Patterns

Figure 9 presents the simulated current field in the My Khe coastal area under the influence of wave conditions during the northeast monsoon. Within a 500-meter nearshore zone, wave-induced currents dominate with high intensity, flowing seaward during both flood and ebb tidal phases.

During flood tide, wave-driven currents exhibit high velocities, reaching up to 0.45 m/s, and are concentrated primarily near the shoreline. These currents transport sediment offshore and generate strong longshore movement, contributing significantly to coastal morphological changes. During ebb tide, the seaward-directed currents also reach velocities of up to 0.45 m/s, further enhancing sediment transport from the beach toward deeper waters.

In offshore areas, tidal currents become dominant, but their magnitudes are generally lower - less than 0.2 m/s - and thus have a limited impact on shoreline morphology. Overall, within the 500-meter nearshore zone during the northeast monsoon, wave-induced currents play a dominant role, exerting strong influence on sediment transport and coastal transformation, while tidal currents are more influential further offshore but with weaker intensity.

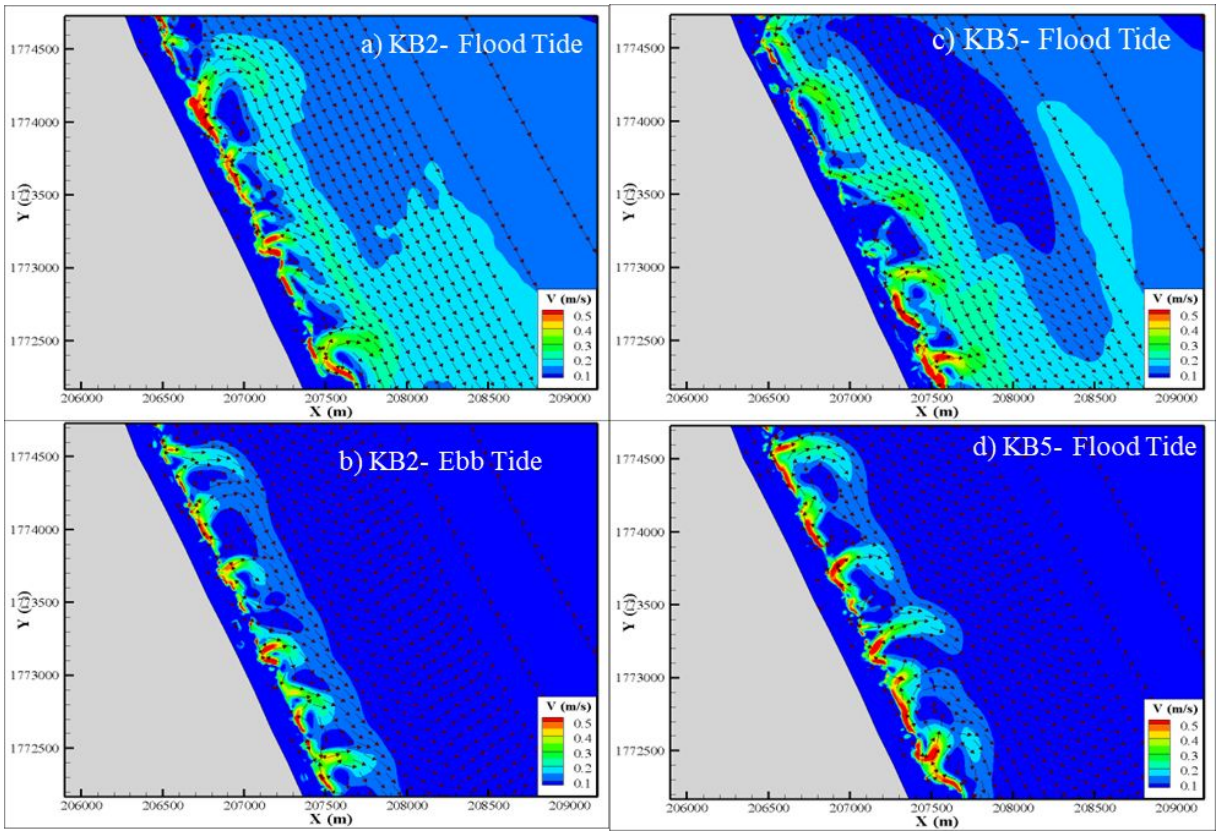

Fig 9. Current field in the My Khe coastal area under northeast monsoon (winter) wave conditions: (a,c) KB2 conditions; (b,d) KB5 conditions.

Figure 10 illustrates the velocity field in the My Khe coastal area under the influence of wave conditions during the southwest monsoon. Compared to the northeast monsoon, nearshore current intensity is significantly reduced, reflecting a marked shift in the region's hydrodynamic processes. Nearshore currents exhibit low velocities, generally below 0.2 m/s, and the previously prominent seaward-directed flows are no longer clearly observed—contrasting strongly with the northeast monsoon period, when strong offshore-directed currents were evident.

The reduction in wave energy during the southwest monsoon is a key factor, as it substantially diminishes wave impacts on the nearshore zone. This leads to weakened current activity and limited sediment transport offshore.

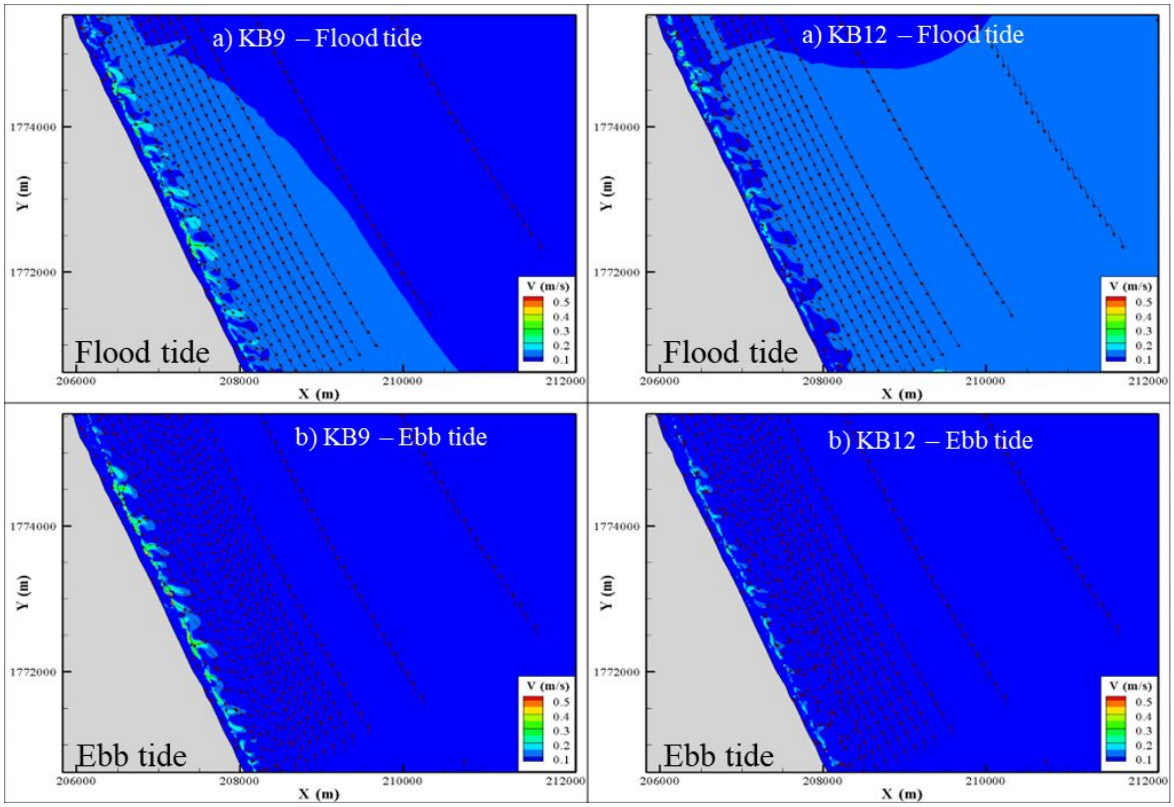

Fig. 10. Velocity field in the My Khe coastal area under southwest monsoon (summer) wave conditions: (a, c) KB9 conditions; (b, d) KB12 conditions

This phenomenon helps explain why mega cusps features are less pronounced during the southwest monsoon - the cusp amplitudes are smoothed, and the troughs are infilled by hydrodynamic weaker conditions - compared to the northeast monsoon. The contrasting impacts of the two monsoon seasons on My Khe Beach highlight that the southwest monsoon induces minimal morphological changes, thereby contributing to shoreline stability and reducing the risk of erosion caused by strong wave and current forces.

3.4 Nearshore bed shear stress Distribution

The My Khe beach area in Vietnam is characterized by notable geographical and climatic features, particularly with strong wave action, especially during the winter months (Figure 11a-b). In winter, bed shear stress increases significantly, with certain areas recording bed shear stress (τ_b) levels up to 4 N/m². This reflects the higher wave energy and current strength prevalent during winter, resulting in considerable bed disruption, sediment movement, and beach erosion. Winter at My Khe is marked by more intense wave action, causing important changes to the beach morphology, altering seabed structure, and influencing sedimentation processes. These changes are critical factors to consider in coastal protection studies and resource management, aimed at developing strategies to mitigate the impacts of climate change and the seasonal dynamics affecting seabed processes.

In contrast, during the summer (Figure 11c-d), bed shear stress remains lower and more evenly distributed, typically ranging from 1 to 2 N/m², and becomes nearly negligible under the mildest case (Figure 11d). This reflects more stable wave and current conditions in summer, with less intense wave energy and current strength compared to winter.

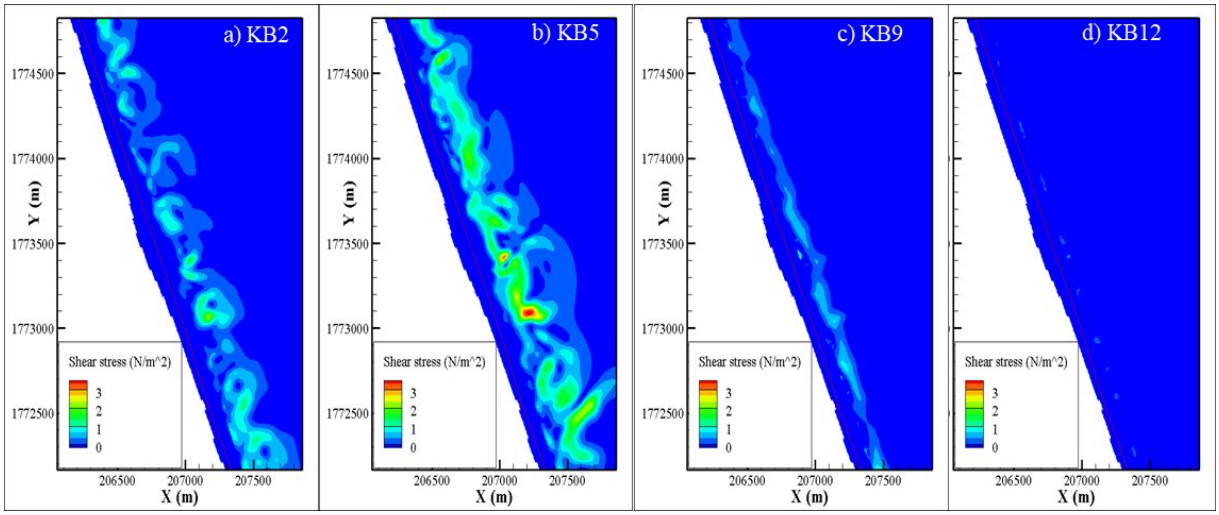

Fig 11. Numerically simulated nearshore bed shear stress τ_b (N/m²) under representative winter (a–b) and summer (c–d) wave conditions: (a) KB2: Hs = 2.0 m, Tp = 8.0 s, Dir = 45°; (b) KB5: Hs = 2.5 m, Tp = 8.0 s, Dir = 60°; (c) KB9: Hs = 1.5 m, Tp = 6.0 s, Dir = 135°; (d) KB12: Hs = 1.0 m, Tp = 6.0 s, Dir = 150°.

Although summer still experiences wave action, the intensity is significantly lower compared to winter. The differences in bed shear stress between winter and summer are crucial for understanding the dynamic processes at My Khe beach.

4. Discussions

4.1 Monsoon-driven Hydrodynamic (/Morphodynamic) behavior

The seasonal monsoon system exerts a dominant influence on wave characteristics along the My Khe coastline. During the ENE monsoon (winter), waves typically approach the shore with higher energy and a more perpendicular angle of incidence. Significant wave heights during this period often range from 1.5 to 2 meters, generating strong longshore and return currents that enhance offshore sediment transport and promote erosional processes, particularly in embayed or concave shoreline segments. In contrast, the ESE monsoon (summer) is characterized by lower wave heights (around 1 meter) and a more oblique angle of wave approach. These conditions reduce the energy flux toward the shore and favor sediment deposition, leading to the smoothing or even disappearance of mega cusps features and contributing to beach accretion.

The presence of Cu Lao Cham Island plays a critical role in modulating wave energy distribution along the coast through a natural wave sheltering effect. During the ENE monsoon, the island creates a localized sheltered zone due to the quasi-normal wave incidence, resulting in a diffraction pattern similar to that produced by a detached breakwater. This leads to the formation of tombolo-like or mega cusps features in the onshore direction. Conversely, during the ESE monsoon, the oblique wave approach results in a broader and more continuous sheltered zone that extends across much of My Khe Beach. This extensive protection reduces wave energy exposure and enhances sediment accumulation, particularly in the central and southern sections of the beach.

Bed shear stress is a key parameter in determining sediment mobilization and transport. The numerical simulations reveal a clear seasonal contrast in bed shear stress patterns. During the ENE monsoon, elevated wave energy and stronger longshore currents generate higher bed shear stress values, particularly in exposed zones, which facilitates sediment erosion and the development of megacusps. In contrast, the ESE monsoon is associated with lower current velocities and reduced bed shear stress, especially in thesheltered zones. These conditions favor sediment deposition and embayment infilling, contributing to the seasonal expansion of the beach profile. The spatial variability in bed shear stress, driven by both wave direction and

sheltering effects, underscores the complex interplay between hydrodynamic forcing and morphological response.

At the same time, these bed shear stress estimates must be interpreted with caution. They are influenced by spatial resolution (bathymetric smoothing, Manning or bottom-friction parameterization) and by temporal resolution constraints imposed by the CFL condition. At meter-scale resolution, sub-grid variability in roughness and turbulence cannot be explicitly resolved, and bed shear stress should therefore be regarded as an effective, bulk indicator of hydrodynamic forcing rather than a point-scale representation of near-bed processes.

4.2 Implications and Limitations

This study highlights how seasonal monsoon forcing controls the formation and decay of mega-cusps at My Khe Beach, providing information of direct relevance to coastal planning and management. Understanding the timing and magnitude of seasonal erosion and accretion is essential for designing adaptive, climate-resilient coastal protection measures and for anticipating future shoreline change.

The validated Delft3D model reproduced the local hydrodynamic conditions with good accuracy and revealed a clear relationship between wave energy and seaward-directed return currents. During the ENE monsoon, high-energy waves (Hs ≈ 1.5–2 m) and strong north-to-south longshore currents (up to 0.45 m s^{-1}) intensify offshore sediment transport, deepening the embayments of mega-cusps and promoting erosion. Conversely, the calmer ESE monsoon (Hs ≈ 1 m; longshore currents < 0.2 m s^{-1}) favors onshore sediment transport and the partial smoothing or erasure of cusp morphology.

These seasonal contrasts generate a cyclic pattern of erosion and recovery and a non-equilibrated, hysteretic shoreline response, resulting in a long-term erosional trend. Such insights are valuable for hazard mitigation and nourishment planning, as they identify periods of heightened vulnerability and potential windows for beach recovery.

The presence of Cu Lao Cham Island further modulates wave energy, acting as a natural detached breakwater. During the ENE monsoon the island produces a narrow, quasi-normal wave-sheltered zone that encourages the development of tombolo-like features and mega-cusps. In summer, when waves arrive at a more oblique angle, the sheltered zone broadens and promotes wider beach accretion. Recognising these sheltering effects is critical for designing future coastal structures and for predicting the spatial variability of erosion risk along My Khe Beach.

Despite these advances, several constraints should be noticed. First, storm-surge events were not explicitly modelled in the current study. Although Typhoon Noru (2023) produced significant morphological change, the lack of high-resolution observations during such extreme events limits our ability to quantify their contribution to sediment transport and shoreline adjustment. Future research should integrate storm-surge scenarios through targeted field campaigns, remote sensing, or hindcast modelling.

Second, the analysis is limited by the availability of bathymetric data. Surveys were conducted in January 2023 and January 2025, with only a single intermediate dataset in May 2024. This restricts the model's ability to capture intra-annual morphological change and limits the temporal resolution of seasonal variability. Although the relatively low hydrodynamic energy during the study period lessens the likelihood of major short-term morphological adjustments - making the use of a static bathymetry acceptable for model verification - more frequent bathymetric monitoring would greatly enhance confidence in long-term trend assessments.

Third, the results should be interpreted in light of the inherent limitations of the modeling framework. The Delft3D setup is based on depth-averaged shallow-water equations, which provide an efficient and robust representation of large-scale nearshore hydrodynamics but necessarily rely on parameterizations to represent highly complex physical processes. In particular, nearshore bed shear stress is strongly influenced by turbulence generated by wave breaking, swash–surf interactions, and strong vertical velocity gradients. These processes

involve non-hydrostatic pressure distributions, pronounced nonlinearities, large wave steepness, and intense energy dissipation, which are only partially captured within a hydrostatic, depth-averaged formulation.

5. Conclusion and perspectives

This study demonstrates how the seasonal monsoon regime and the sheltering effect of Cu Lao Cham Island jointly govern the lifecycle (formation, evolution, and decay) of mega-cusps at My Khe Beach. Based on satelitte and field observations, a numerical (Delft3D) model has been validated revealing a cyclical pattern of wintertime erosion and summertime recovery, reflecting the interaction between high-energy northeast monsoon waves and calmer southwest monsoon conditions.

These findings emphasize that shoreline changes in monsoon-dominated settings are strongly non-linear and spatially variable, highlighting the need for site-specific monitoring and adaptive management. While the present work focused on seasonal variability of flow dynamic under typical conditions, the next step is to extend modelling to extreme events and higher-resolution bathymetric datasets, in order to better quantify the role of storms and short-term morphological adjustments.

By clarifying the seasonal mechanisms and highlighting knowledge gaps, this research provides a robust foundation for future coastal protection strategies and for refined numerical studies of sediment dynamics in coastal systems influenced by storm surges, cyclonic activity, monsoons, and both tropical and extra-tropical climatic scenarios.

Building on these findings, future work will aim to better distinguish the respective roles of wave height and wave direction in driving erosion and deposition processes during the ENE and ESE monsoon seasons. This will involve a more detailed examination of sediment transport dynamics, including how variations in wave energy and incident angles influence sediment pathways and morphological responses along the My Khe shoreline.

A long-term perspective will also be adopted by incorporating multi-seasonal and pluri-annual datasets. This approach will help identify persistent trends and interannual variability in coastal evolution, offering a more robust understanding of the cumulative effects of seasonal forcing on shoreline stability.

In addition, the study will explore the impact of extreme wave conditions, which were discussed in the current work's discussion section. While field measurements during such high-energy events pose significant risks, the validated numerical model provides a valuable tool for simulating and predicting sediment behavior under these extreme scenarios. This predictive capability is essential for proactive coastal management and hazard mitigation.

To further validate model outputs and improve the accuracy of erosion and accretion zone identification, future work may also incorporate sediment tracing techniques. Specifically, methods based on the mapping of sediment-associated radionuclides could be employed. Given the contrasting energy environments along My Khe Beach—ranging from sheltered zones with low wave energy to highly exposed areas—this site presents promising conditions for applying such techniques to validate sediment deposition and erosion patterns. In parallel, a more detailed quantification of absolute bed shear stress, including extended sensitivity analyses and higher-order process representation, will also be addressed in future studies to strengthen understanding of the links between hydrodynamic forcing and morphological response.

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Competing interests

No competing interest for all authors.

Data availaibility

Data are available upon reasonable request.

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