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Assessment of the impact of sediment dispersion on coral reef ecosystems caused by submarine cable installation in the Con Dao Archipelago, Vietnam

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ABSTRACT

This study evaluated the impact of sediment dispersion from submarine cable installation on coral reef ecosystems in Con Dao Archipelago, Vietnam using the MIKE 3 hydrodynamic model. It analyzed coral reef distribution and turbidity spreading under different monsoon conditions. Results showed that during the Northeast monsoon, turbidity primarily affected the southern island regions with few coral reefs, while the Southwest monsoon caused significant impacts on reefs along the western coast, especially near Hon Tre Lon and Hon Troc Islands along the cable route. Maximum turbidity concentrations were recorded at 0.00028 kg/m³ (surface), 0.0033 kg/m³ (mid-depth), and 0.12 kg/m³ (near-seabed), with an impact radius of ~3 km. Coral reefs along the east coast and Hon Bay Canh Island were minimally affected. These findings suggest that cable installations should occur during the Northeast monsoon to mitigate ecological impacts.

Keywords: Environment, turbidity, coral reefs, monsoon dynamics, subsea infrastructure, impact assessment.

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Introduction

Coral reef ecosystems are among the most productive and biodiverse environments on Earth, playing a pivotal role in maintaining ecological balance and supporting human well-being. They provide critical habitats for thousands of marine species, forming complex trophic networks and contributing substantially to global biodiversity conservation [1, 2]. Beyond their ecological significance, coral reefs offer a range of essential ecosystem services, including coastal protection against erosion, storm surges, and tsunamis. They also support fisheries, tourism, and biomedical research through their rich bioactive compounds and aesthetic value [3, 4]. In addition, coral reefs act as natural water filters, improving seawater quality, and contribute to climate regulation by sequestering atmospheric CO_2, which is particularly important in mitigating climate change impacts [5]. Despite these vital functions, coral reefs are undergoing unprecedented degradation due to climate change, ocean acidification, and direct anthropogenic pressures, including pollution, sedimentation, and coastal development activities [6].

Among human-induced stressors, activities such as marine resource extraction, dredging, land reclamation, and submarine cable installation have increasingly impacted coral reef health by elevating water column turbidity [7]. Elevated turbidity reduces light penetration, thereby impairing the photosynthetic efficiency of symbiotic zooxanthellae algae, which provide the primary energy source for corals [8]. Sediment deposition on coral surfaces can further impede respiration and metabolic processes, potentially leading to tissue necrosis, while prolonged turbidity events reduce reproductive success and threaten the sustainability of dependent species, thereby undermining the broader ecological integrity of reef systems [9]. Although numerous studies have characterized sediment impacts under controlled laboratory and field conditions, the availability of high-resolution, in situ data during actual dredging or construction operations near coral reefs remains limited, which introduces uncertainty into environmental risk assessments and complicates management decisions.

Turbidity, defined as the optical property of a water column that scatters and absorbs light, is primarily controlled by suspended sediment concentrations but is also influenced by plankton, colored dissolved organic matter, and other particulate materials [10, 11]. In shallow tropical and subtropical waters, suspended sediments are often the dominant factor determining light attenuation, while natural processes, including wind-driven waves, tidal currents, and unidirectional flows, influence sediment resuspension and transport [12, 13]. Anthropogenic activities frequently exacerbate turbidity events, amplifying their negative impacts on coral physiological processes, growth, and reproductive cycles.

Hydrodynamic models have emerged as indispensable tools for understanding and predicting these complex interactions between water movement, sediment transport, and pollutant dispersion [14, 15]. By providing a numerical framework to simulate spatial and temporal variability in currents, tides, and turbulence, these models allow accurate prediction of suspended sediment transport pathways and turbidity plumes [16–19]. For instance, the MIKE 3 model has been successfully applied to simulate turbidity dispersion resulting from sediment dumping and dredging activities, enabling assessments of how hydrodynamic forces interact with suspended particles to affect coral reef environments. Integrating hydrodynamic modeling with remote sensing and field observations further enhances the accuracy of suspended sediment concentration estimates under varying wind, tide, and oceanographic conditions, as demonstrated in studies in the Mekong River estuary and Red River Delta. These models also allow scenario-based evaluations, such as quantifying the impacts of typhoon-induced currents or construction activities on turbidity dispersion, thereby informing coastal management strategies, dredging regulations, and coral conservation measures [20–24].

Building upon these advances, the present study employs the MIKE 3 hydrodynamic model to simulate turbidity dispersion under various submarine cable installation scenarios. By quantifying turbidity concentrations in the impacted areas, this work provides a scientific basis for assessing potential effects on coral reef ecosystems in the Con Dao Archipelago, bridging the gap between experimental knowledge and real-world environmental management (Fig. 1). This approach supports evidence-based decision-making for minimizing ecological impacts, ensuring sustainable development of coastal infrastructure, and preserving the long-term health of coral reef ecosystems.

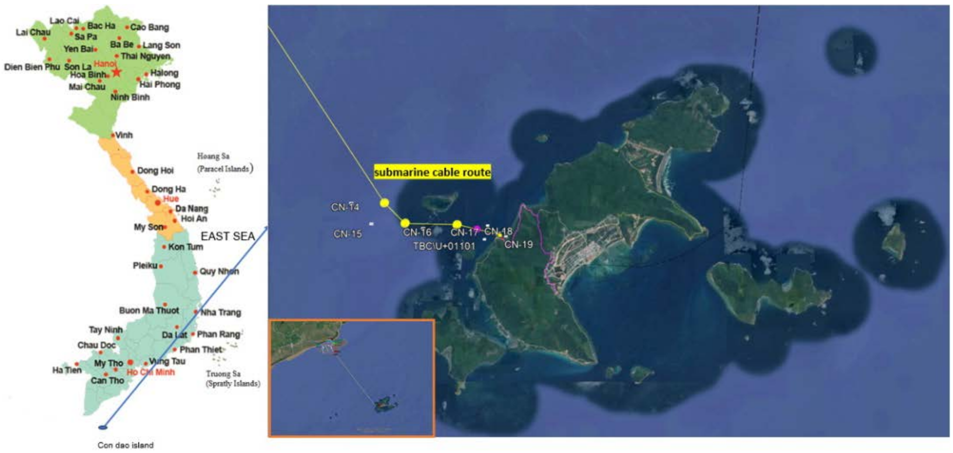

Figure 1. Study area

Materials and methods

Materials

Topographic Data: The study utilizes seabed topographic maps at a 1:10,000 scale for the southeastern coastal region of Vietnam, derived from the national-level research project "Scientific foundation development and spatial planning recommendations for the Phu Quoc-Con Dao marine area to support sustainable development" [25]. These maps are supplemented with high-resolution bathymetric survey data at a 1:5000 scale from the project area designated for submarine cable installation. All topographic datasets have been harmonized to conform to the national vertical reference system.

Wave Data: Wave parameters, including wave height, period, and propagation direction, were obtained from observations at the Con Dao Hydrometeorological Station (Fig. 2). These data were further supplemented with global wave datasets sourced from the CoastWatch platform [26].

Wind Data: The study area is markedly influenced by the marine atmospheric system. Accordingly, the research team employed daily mean wind data recorded at the Con Dao Meteorological Station for analysis (Fig. 2).

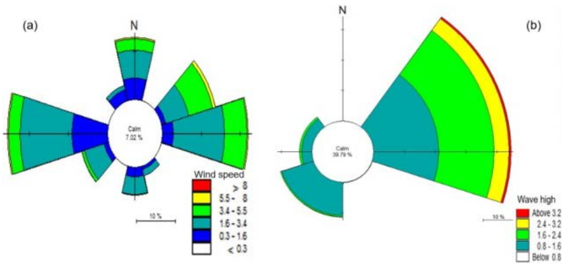

Figure 2. Wind (a) and Wave (b) mapping at Con Dao station

Water Level: The study incorporated observed water level data from 2022 at the Con Dao station to support the calibration and validation of the hydraulic model.

Sediment Data: Based on the analysis of sediment samples from the project area, mud acts as the dispersing material, while sand serves as the settling material. The suspended mud sediment has a concentration of 1,050 kg/m³, a settling velocity of 0.015 m/s, and a critical shear stress of 0.02 N/m² (playing a key role in diffusion). In contrast, suspended sand sediment has a concentration of 2,650 kg/m³, a settling velocity of 0.3 m/s, and a critical shear stress of 0.5 N/m².

Methods

The study aims to evaluate the current distribution of coral reef ecosystems in the Con Dao Archipelago region and to assess the areas of coral reefs impacted by turbidity resulting from dredging activities associated with the installation of submarine cables in the study area.

This study used the MIKE 3 model to simulate turbidity dispersion in the study area during the monsoon. The first stage of the simulation involves collecting data, including wave, wind, depth, and water level. Then, the model was set up for calibration and validation using input data such as tidal conditions and monsoon patterns. After simulating the hydrodynamics, the result can be used for turbidity propagation simulations. The results of the coral reef distribution map in the study area were compared with the turbidity simulation results to assess the coral reef areas affected by the submarine cable installation activities. The research methodology is outlined in the following schematic diagram (Fig. 3).

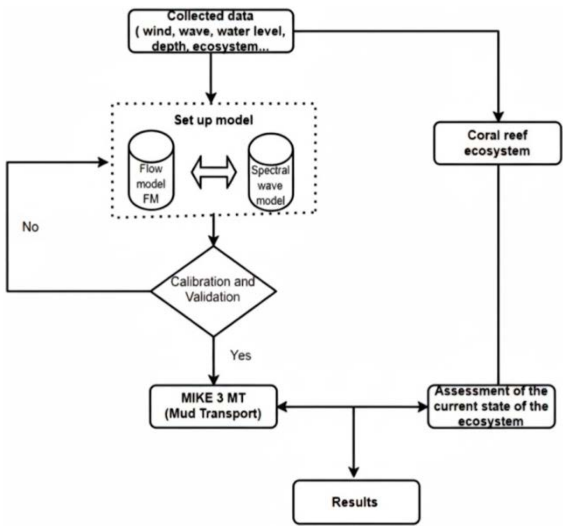

Figure 3. Study approach flowchart

The MIKE modeling system, developed by the Danish Hydraulic Institute (DHI), is a comprehensive suite of numerical models designed to simulate various aspects of water environments, including rivers, lakes, coastal zones, and marine systems. It supports both one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) hydrodynamic modeling, and is widely used for applications such as flood forecasting, sediment transport, water quality, and environmental impact assessments. MIKE models are based on robust physical and numerical principles, allowing for accurate simulation of complex hydrological and hydraulic processes under various scenarios [27, 28].

Results and discussion

Spatial distribution and extent of coral reef ecosystems in the Con Dao Archipelago

The coral reef ecosystem is highly developed in the region surrounding Con Dao National Park, encompassing 342 species, 61 genera, and 17 families, with dominant coral taxa including *Acropora, Porites, Pachyseris, Montipora*, and *Pavona*. Research findings reveal that 74.2% of coral reefs exhibit high coverage, 23% display moderate coverage, and only 2.8% are classified as having low coverage. The spatial distribution of the coral reef ecosystem is depicted in Figure 4.

In general, the fringing reefs in this area (Fig. 5) are of medium size, with a width of approximately 50–100 meters, and are divided into five zones as follows:

Zone 1: Extending from the intertidal zone to a depth of 2 meters, with a width of about 11–12 meters. The seabed consists of gravel and rocks, featuring scattered coral colonies in massive and encrusting forms, along with algae attached to rocks.

Zone 2: Approximately 20 meters wide and located at a depth of 3 meters. The seabed is primarily composed of pebbles and gravel, with a diverse composition of coral species and various colony morphologies.

Zone 3: Spanning 15–30 meters in width and situated at depths of 2–7 meters. The seabed is made up of dead coral, coarse sand, and organic sediments of various origins. Live coral in this zone has the highest coverage, demonstrating strong dominance.

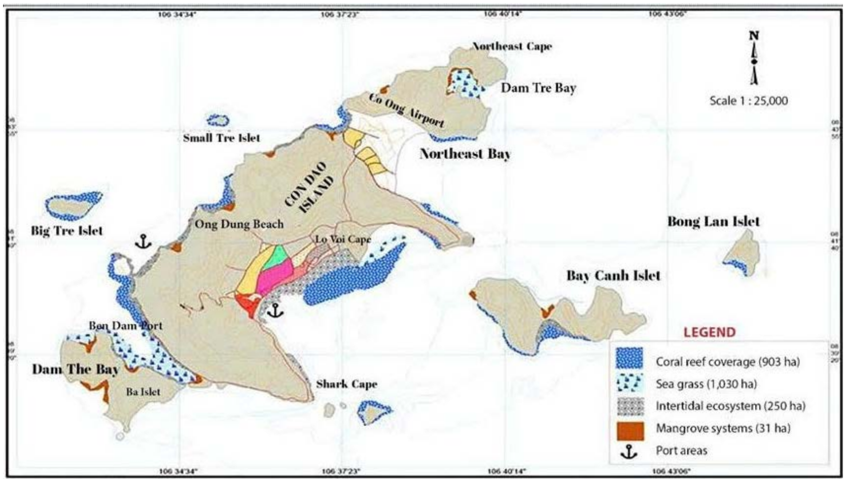

Figure 4. The distribution of marine ecosystems in the Con Dao Island area [29]

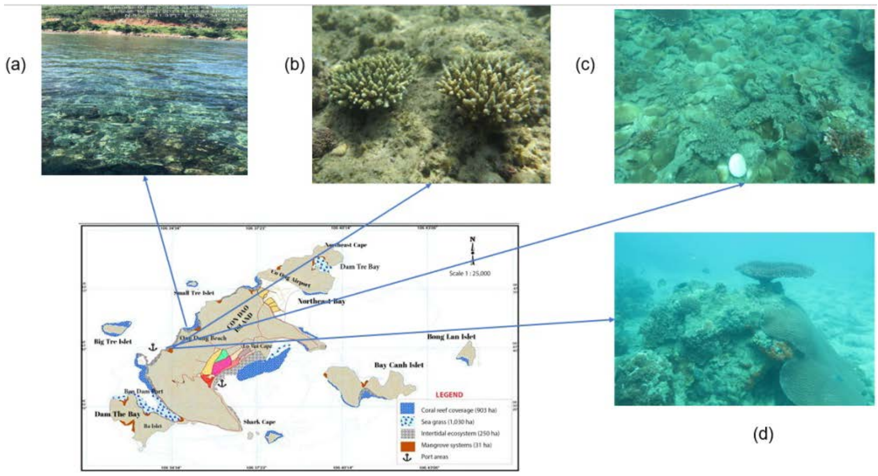

Figure 5. The distribution of coral reefs by depth [29]

Zone 4: About 20–60 meters wide and found at depths of 6–13 meters. The seabed consists of dead coral and mud. Soft corals and gorgonian corals are well-developed, while hard corals are sparsely distributed.

Zone 5: Located at the reef base, with a soft, muddy seabed. Live coral is significantly reduced, with the presence of soft corals and gorgonian corals at low densities. Scattered solitary hard corals and Halophila algae are also distributed in this zone.

Model setup

The study established a high-resolution computational grid to simulate hydrodynamic (HD) processes and the dispersion of suspended sediments (MT) within the Con Dao Archipelago. The model domain covers an area of approximately 900 km^2 and is discretized into 9,562 grid cells and 6,235 computational nodes, providing sufficient spatial resolution to capture fine-scale variations in currents, tidal dynamics, and sediment transport. The grid design ensures accurate representation of coastal topography, bathymetry, and key geomorphological features, which are critical for simulating sediment resuspension and turbidity dispersion under varying hydrodynamic conditions. The spatial extent and configuration of the computational domain are illustrated in Figure 6.

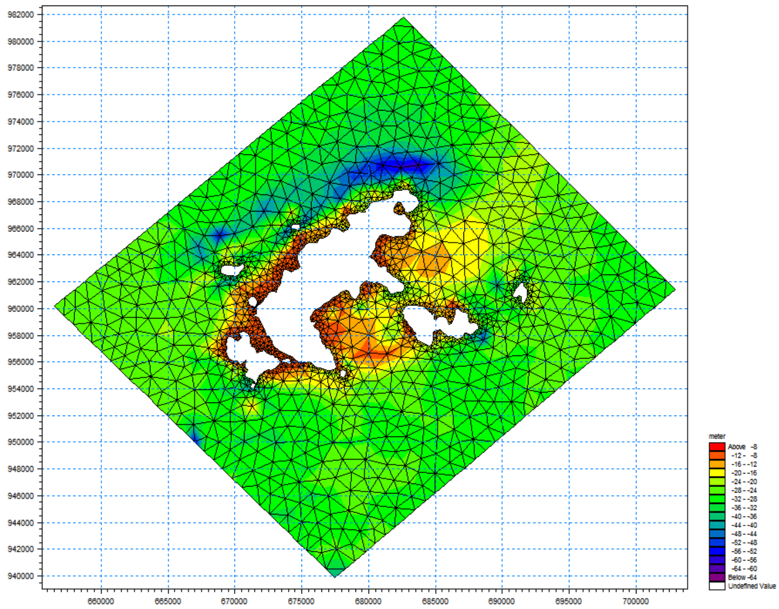

Figure 6. Computation grid of study area

The cable installation and burial process was conducted using a specialized cable burial machine, achieving a depth of 3 meters and a width of 2 meters, following the submarine cable route within the study area. Accordingly, the study employed this dataset as input parameters for model calibration and development. The modeling framework incorporated the seabed dredging plan, characterized by a dredging volume of 6,000 m³, evenly distributed over a 10-kilometer section along the designated route near Con Dao Island. The model boundary conditions are presented in the Table 1.

Table 1. Model boundary conditions

No.	Boundary Condition	Description
1	Wind Data	Extreme wind values from NE and W directions, with average wind speeds of 3.63 m/s and 3.43 m/s, respectively
2	Water Levels	Boundary conditions derived from global sea level data using the toolbox module of the MIKE model
3	Wave Data	Extreme wave values from Con Dao hydrometeorological station, with wave heights H = 0.75 m (NE direction) and H = 1.5 m (SW direction).
4	Sediment Data	Suspended mud: Concentration 1,050 kg/m³, settling velocity 0.015 m/s, critical shear stress 0.02 N/m²; Suspended sand: Concentration 2650 kg/m³, settling velocity 0.3 m/s, critical shear stress 0.5 N/m²
5	Simulation Duration	Continuous simulation for 3 months for each monsoon period, with dredging operations occurring for 8 hours per day

Model calibration

The study utilized observed water-level data obtained from the Vung Tau and Con Dao hydrometeorological stations (coordinates: 106°36’E, 8°41’N) to perform both calibration and validation of the hydraulic model. These high-resolution measurements provided a reliable basis for ensuring the accuracy of the simulated hydrodynamic conditions, including tidal fluctuations and seasonal variations in water levels, thereby enhancing the model's capability to predict sediment transport and turbidity dispersion in the study area. Water level data collected from January to February 2022 were utilized for calibration, while data from July to September 2022 were used for validation. The model's performance was evaluated using the Nash-Sutcliffe Efficiency (NSE) coefficient, where values between 0.7 and 1.0 are indicative of satisfactory agreement for hydraulic simulations. The comparison of simulated and observed water levels at the Con Dao station resulted in an NSE value of 0.89 (Fig. 7). Accordingly, the calibrated parameter set, including a Manning roughness coefficient of M = 32, was validated as reliable for subsequent hydraulic model simulations.

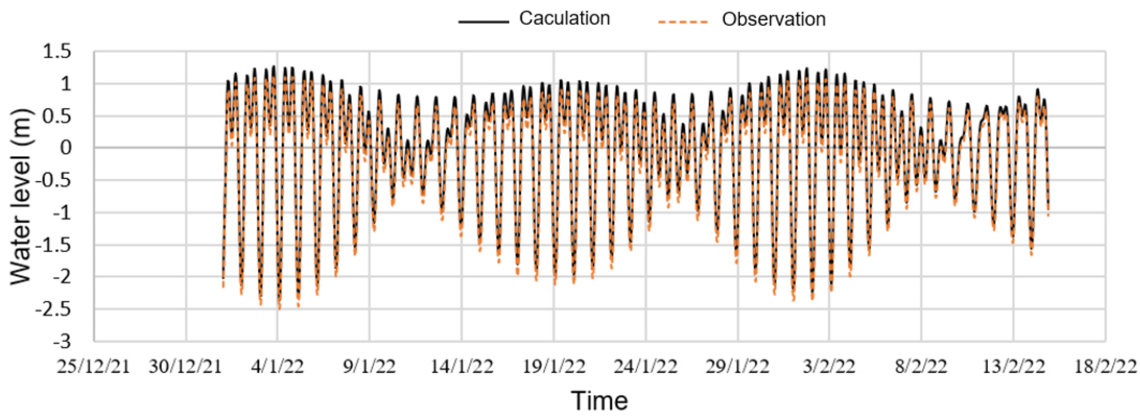

Figure 7. Comparison of simulated and observed water levels during model calibration

Model validation

The model validation process employed the calibrated parameter set from the previous stage to simulate hydraulic conditions over a different time period, ensuring the stability and reliability of the hydraulic model (Figs. 8, 9). Specifically, the study used the calibrated parameters, including a Manning's roughness coefficient of M = 32, to validate the model over the period from July 1, 2022, to August 1, 2022. The validation yielded a Nash-Sutcliffe Efficiency (NSE) coefficient of 0.86, indicating satisfactory model performance. With these results, the calibrated and validated parameter set, characterized by a robust NSE, is deemed suitable for simulating turbidity dispersion resulting from dredging activities associated with submarine cable installation.

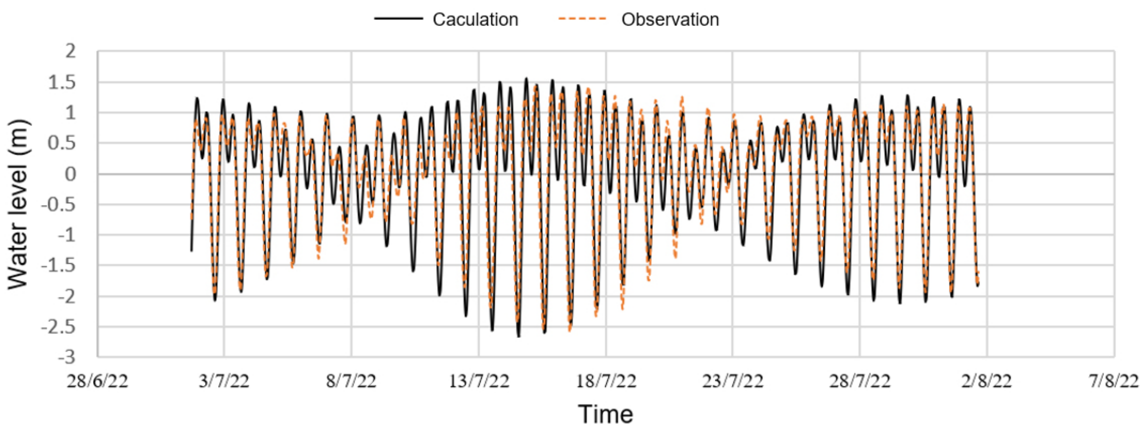

Figure 8. Comparison of simulated and observed water levels during model validation

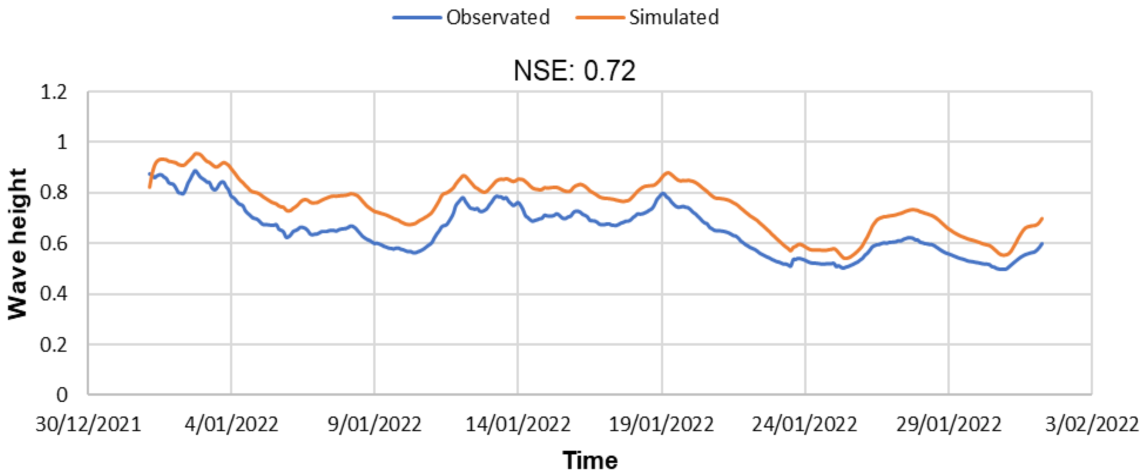

Figure 9. Comparison of simulated and observed wave height during model validation

Turbidity dispersion results

To assess the potential impacts of elevated turbidity on coral reef ecosystems, this study developed a series of numerical simulation scenarios aimed at quantifying the dispersion of suspended sediments generated during dredging operations for submarine cable installation. These scenarios were designed to capture seasonal variations in hydrodynamic conditions and their influence on sediment transport in the vicinity of Con Dao Island.

Scenario 1: This scenario simulated turbidity dispersion associated with dredging activities conducted during the Northeast Monsoon season. The dredging operation involved a total sediment volume of 6,000 m³, which was assumed to be evenly released along a 10-kilometer section of the planned cable route. The simulation accounted for seasonal currents, wind patterns, and tidal fluctuations typical of the Northeast Monsoon, providing insights into the spatial extent and temporal evolution of the turbidity plume under these hydrodynamic conditions.

Scenario 2: This scenario addressed turbidity dispersion during the Southwest Monsoon season, using the same dredging volume of 6,000 m³ distributed along the identical 10-kilometer cable route. By incorporating the distinct hydrodynamic regime of the Southwest Monsoon, including prevailing currents and wave dynamics, this scenario allowed for comparative assessment of seasonal variations in sediment transport and the potential exposure of nearby coral reef communities to elevated turbidity levels.

Scenario 1

The study employed the MIKE 3 hydraulic model to simulate turbidity dispersion during the installation of submarine power cables from the coastal area of Soc Trang to Con Dao Island. To evaluate turbidity dispersion caused by dredging and cable installation activities, the model simulated turbidity diffusion across different depth layers (surface, middle, and bottom layers) under varying monsoonal conditions. The results of these simulations are presented in the Figure 10.

The simulation results reveal that during the Northeast Monsoon season, turbidity dispersion predominantly shifts southward of the island. As a result, the eastern coastal zone, characterized by high coral reef biodiversity, remains largely unaffected by turbidity generated from submarine cable installation activities. Conversely, coral reef systems around Hon Tre Lon and Hon Troc experience notable impacts from turbidity dispersion, with concentrations in these areas reaching as high as 0.07 kg/m³.

Due to the seabed composition primarily consisting of rock and sand, with a median grain size of sediment (D_{50} = 0.36 mm), the radius of turbidity influence is relatively small, approximately 3 km. The maximum turbidity concentration in this area varies across different water layers, reaching approximately 0.00028 kg/m³ at the surface, 0.0033 kg/m³ at the mid-depth, and 0.075 kg/m³ at the near-seabed.

The coral reef ecosystems in the western coastal area of the island and the nearshore region of Ben Dam Port, distributed at depths of less than 6 meters, are virtually unaffected by turbidity resulting from submarine cable installation activities in the study area.

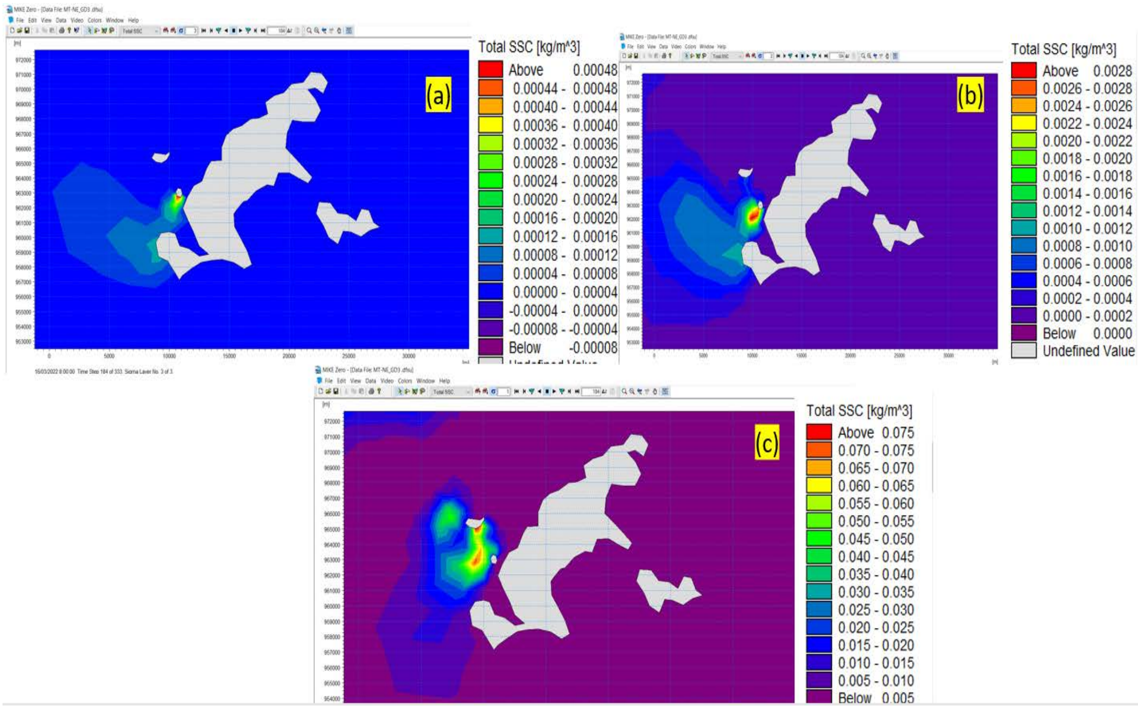

Figure 10. Distribution of turbidity concentration by depth in Northeast (a) Surface layer, (b) Middle layer, (c) Bottom layer

Scenario 2

Based on the simulation results of hydrodynamic conditions and turbidity dispersion during the Southwest Monsoon season, it was observed that in the area of submarine cable installation, turbidity concentrations exhibit a propagation trend in the north-south direction along the island. The maximum turbidity concentration at the surface layer in the cable installation area was approximately 0.00028 kg/m³, while concentrations in the middle and bottom layers reached 0.0033 kg/m³ and 0.12 kg/m³, respectively, with an impact radius of approximately 3 km.

The turbidity concentration distribution map reveals that coral reefs located along the western coast of Con Dao Island are highly susceptible to the turbidity propagation trend during the Southwest monsoon. Among the impacted regions, Hon Troc Island is identified as the most significantly affected area. Conversely, coral reef ecosystems distributed along the eastern coast of the island and in the vicinity of Hon Bay Canh Island are largely unaffected by turbidity dispersion resulting from submarine cable installation activities.

The coral reef ecosystem in the Hon Tre Lon Island area is also subject to turbidity dispersion, with concentrations in this region reaching approximately 0.008 kg/m³ (Fig. 11). However, the turbidity levels associated with cable installation during this period are lower compared to those observed during the Northeast monsoon season.

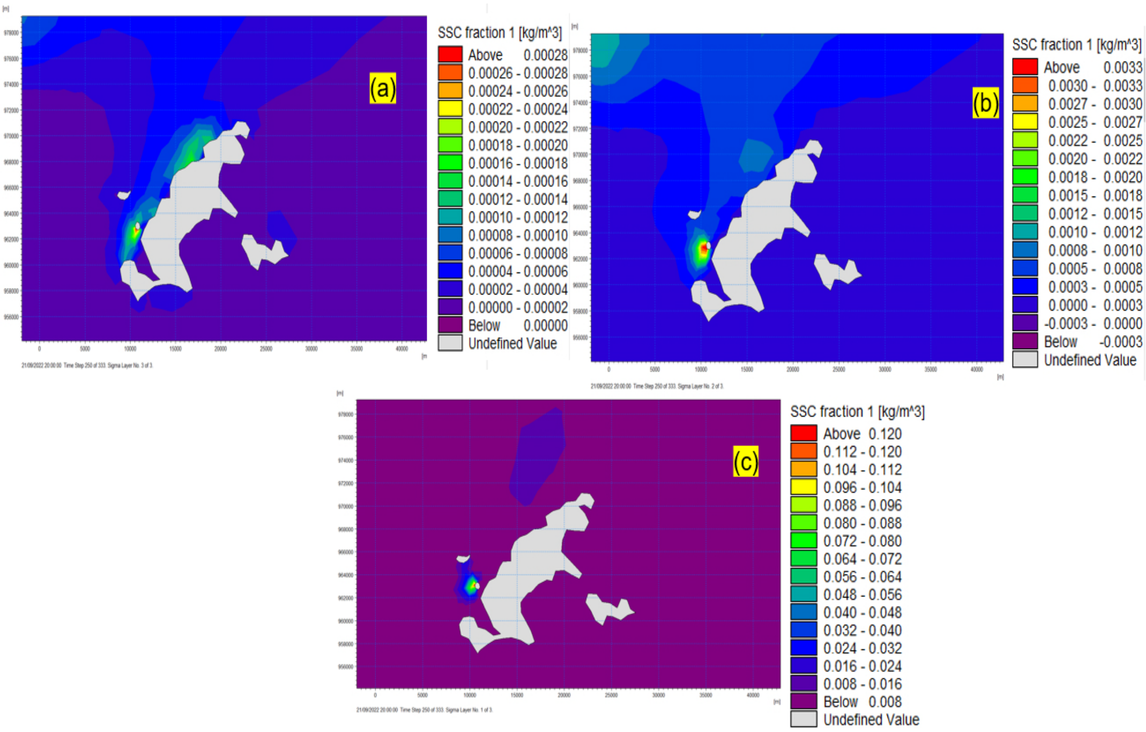

Figure 11. Distribution of turbidity concentration by depth in Southwest (a) Surface layer, (b) Middle layer, (c) near-seabed layer

Turbidity impact assessment on coral reefs

To assess the impact of turbidity levels resulting from dredging and submarine cable installation activities, the study selected specific monitoring locations to extract suspended sediment concentration data, as illustrated in the Figure 12 and Table 2.

The simulation results show that at location P5, turbidity dispersion from submarine cable installation activities has no impact. During the Northeast Monsoon season, bottom-layer turbidity concentrations at locations P1 and P2 exceed the threshold, directly affecting coral reef ecosystems. Meanwhile, during the Southwest Monsoon season, turbidity concentrations at locations P2, P3, and P4 exceed the threshold, posing potential risks of negative impacts on coral reefs.

The quantitative evaluation of turbidity concentrations on coral growth has been highlighted in studies such as Lillian and Megan, indicating that turbidity levels exceeding 0.0032 kg/m^3 can lead to coral mortality or bleaching in adult corals. For juvenile corals, turbidity levels above 0.01 kg/m^3 result in reduced growth rates. The correlation between turbidity concentration and its impact on coral is presented in the Table 3.

Based on the extracted turbidity concentrations at monitoring locations and their comparison with the impact thresholds of turbidity on coral reefs, it was observed that at location P2, during both monsoon periods (the dredging site along the cable route), the highest turbidity concentration exceeded 0.0062 kg/m^3. This level can potentially cause mortality in adult corals and hinder the growth of juvenile corals. However, the impact range of this turbidity was limited to approximately 0.2 km.

During the Northeast monsoon period, location P1 recorded a sediment concentration of 0.0022 kg/m^3, which corresponds to the threshold level capable of causing mortality in both adult and juvenile corals. Meanwhile, during the Southwest monsoon period, location

P3 exhibited a sediment concentration of 0.0054 kg/m^3, reaching the threshold that impacts the ecosystem of adult coral reefs. Other locations, however, had sediment concentrations within the safe range for coral reef development.

Figure 12. Turbidity concentration monitoring location

Table 2. Turbidity concentrations at monitoring locations (kg/m^3)

Location	Northeast monsoon season			Southwest mooson season		
	Surface layer	Middle layer	Bottom layer	Surface layer	Middle layer	Bottom layer
P1: (8.643518°; 106.546234°)	0.00024	0.0012	0.0033	0.00004	0.0005	0.0008
P2: (8.678857°; 106.558347°)	0.00048	0.0028	0.0060	0.00028	0.0035	0.0062
P3: (8.707987°; 106.585650°)	0.00008	0.0002	0.0007	0.0002	0.0032	0.0054
P4: (8.734458°; 106.621369°)	0.00004	0.0002	0.0005	0.00014	0.0005	0.0035
P5: (8.676855°; 106.612257°)	0.000001	0.000001	0.000002	0.000001	0.000001	0.000003

Table 3. The impact of turbidity on coral growth [30]

No.	Phenomenon/Organism	Suspended sediment (kg/m^3)	Level of impact
1	Adult coral	≥ 0.0032	Bleaching/Tissue necrosis
2	Juvenile coral	≥ 0.01	Reduced growth
3	High level	0.01	Induce chronic stress
4	Severe light attenuation level	0.03–0.1	Cause severe damage
5	Sedimentation rate	≥ 1 (mg/cm^2/day)	Cross-phase impact

Conclusion

The study delineates the spatial distribution of coral reef ecosystems in the Con Dao Archipelago, providing a critical foundation for assessing the impacts of turbidity dispersion associated with submarine cable installation activities on these ecosystems under varying monsoonal conditions.

During the Northeast monsoon season, the spatial extent of turbidity-induced impacts on coral reef ecosystems in the Con Dao Archipelago is notably reduced compared to the Southwest monsoon season. This reduction is attributed to the southward propagation of turbidity concentrations during the Northeast monsoon, primarily affecting regions with limited coral reef distribution.

Coral reefs in the vicinities of Hon Tre Lon and Hon Troc Islands are subjected to significant impacts from turbidity dispersion during both monsoonal periods, as these islands are located in close proximity to the submarine cable installation corridor. Conversely, coral reefs along the western coast of Con Dao island are predominantly impacted during the Southwest monsoon season. Consequently, it is advisable to schedule submarine cable installation during the Northeast monsoon season to mitigate adverse effects of turbidity dispersion on coral reef ecosystems.

The coral reef ecosystems distributed along the eastern coast of Con Dao Island and around Hon Bay Canh Island exhibit negligible susceptibility to turbidity dispersion resulting from submarine cable installation activities.

This study represents a preliminary evaluation of turbidity dispersion impacts on marine ecosystems, predicated on spatial correlation analyses between turbidity dispersion models and coral reef distribution maps. To comprehensively understand the ecological consequences of submarine cable installation, further research is warranted to investigate its long-term effects on the structure, function, and resilience of marine ecosystems.

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