

# Analyzing the Impact of Tidal Currents on Sludge Dispersion in the Coastal Zone of Da Nang City

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DOI: <https://doi.org/10.14796/JWMM.S572>

## ABSTRACT

The demand for designated sites to receive sludge waste from marine and coastal dredging projects is rising in Vietnam. Coastal areas are particularly promising for such purposes. Evaluating the dispersion of submerged sludge in the marine environment is crucial for assessing potential impacts on adjacent ecological zones that require protection. Tidal currents in the proposed discharge area are a significant factor influencing sludge propagation. The results indicate that varying average tidal currents affect horizontal propagation and result in different changes in bottom topography. Simulations demonstrate that underwater mud could dissolve to a great distance from the discharge site when discharged at an average rate of 100,000 m<sup>3</sup>/month. The study utilized the Telemac3D numerical model, which addressed the problem of sludge dispersion through diffusion and convection and incorporated the TOMOWAC module to solve the issue of wave propagation along the coast. The TELEMAC-3D numerical model is used to solve the problem of sediment dispersion through combined diffusion and advection processes, which has been integrated with the TOMOWAC wave propagation model, which simulates wave dynamics in coastal zones. The combined approach is applied to investigate the impact of mean tidal currents on the dispersal of dredged sediment, considering different discharge timing scenarios.

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Nguyen, Q.T., T.D. Ho, Q.H. Phan, and D.V. Trinh. 2026. "Analyzing the Impact of Tidal Currents on Sludge Dispersion in the Coastal Zone of Da Nang City." *Journal of Water Management Modeling* 34: S572. <https://doi.org/10.14796/JWMM.S572> www.chijournal.org ISSN: 2292-6062 © Nguyen et al. 2026



## 1. INTRODUCTION

In recent years, identifying suitable locations for disposal of dredged sludge and construction sites along the coast has been in great demand. Meanwhile, few studies on the above issue have been conducted to find the appropriate sites, especially in coastal zones (Nguyen 2015). One of the best methodologies for solving this problem is to submerge the sludge in coastal zones. Nonetheless, the urban and ecological areas near the seashore zones are affected by the diluted sludge contaminant (Doan et al. 2019). Besides, the problem of plastic waste transmission in the coastal estuary area of Da Nang-Quang Nam has been studied by using a two-dimensional model – DHI’s MIKE 21/3 (Nguyen et al. 2022). The research results have shown that the concentration of plastic waste was mainly distributed in some coastal areas in the northwest of Da Nang city in the summer season. In contrast, in the winter season, the concentration of plastic waste became more intense and widespread, covering the entire Da Nang bay, and extending along the southern coastline. Nguyen and Pham (2024) investigated the propagation and distribution of floating waste in Da Nang bay by a two-dimensional numerical model using MIKE21FM. The research results indicate that during the northeast monsoon season, under the influence of river flows, ocean currents, waves, and tides, the waste tends to drift northwestward within Da Nang bay and accumulates near the coast. Otherwise, waste distribution in Da Nang bay shifts toward the southwest and disperses further offshore during the southwest monsoon season. The submerged sludge primarily contains tiny sediment that rapidly disperses in the nearby aquatic ecosystem. Due to the condition of energetic hydraulic regimes, this muddy sediment can extend to adjacent space. The spread of sludge is influenced by numerous factors, with convection (predominantly the mean tidal flow) and diffusion being the principal ones. According to the construction planning of the Da Nang city government, the port located at Tho Quang dug up discharges and the underground mud. One study on the distribution of submerged sediment at an offshore position around 8 km from the Son Tra peninsula. The results obtained from the paper can be used to assess the recommended release site and the influence of watery mud on the conserved aquatic zones near the Son Tra peninsula. Nguyen et al. (2023) conducted a study of 3D numerical modeling of the dispersion potential of sewage sludge at the proposed submerged site off the coast of Son-Tra peninsula, Da Nang city. The results show that tidal currents play a significant role in the spread of sludge. Specifically, submerged sludge can spread up to 10 km from the discharge center, reaching a concentration of 5 mg/L under the influence of these currents. However, the studies conducted so far have been limited to the use of two-dimensional or three-dimensional hydrodynamic models, without incorporating wave or tidal models.

Accordingly, this study employs a TELEMAC-3D hydraulic model in conjunction with a TOMAWAC wave propagation model to simulate advection-diffusion processes and the dispersion of diluted sludge. These open-source numerical models—widely adopted in recent years across various countries—were originally developed by research institutions in Europe, the United States, and Canada (Hervouet 2007; Lang 2010).

## 2. RESEARCH REGION AND NUMERICAL MODEL

### 2.1 Research region

The research region encompasses the northern part of the Son-Tra peninsula and extends southward to the Cua-Dai estuary in Hoi-An City (see Figure 1). This region spans approximately 55 km along the coastline, with an average width of 45 km from the shore (see Figure 2). The total area covers around 2,374 km<sup>2</sup> and falls within the humid weather region with rainy and dry seasons. The data related to rainfall employed in this study has the following parameters: intensity values between 2,000 and 2,500 mm and unevenly distributed temporally and spatially. The rainy season, occurring predominantly from September to December, accounts for approximately 80% of the yearly precipitation. The impact of wind acting on the open sea surface of the region, considering the hydrodynamic flow regime, is also considered (see Figure 3).

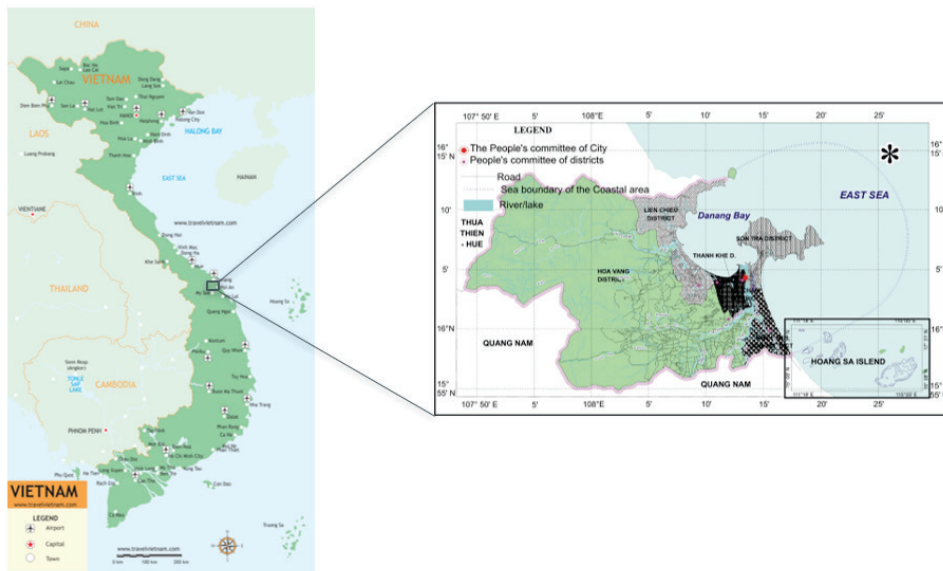


Figure 1 Location of Da Nang city, Viet Nam.

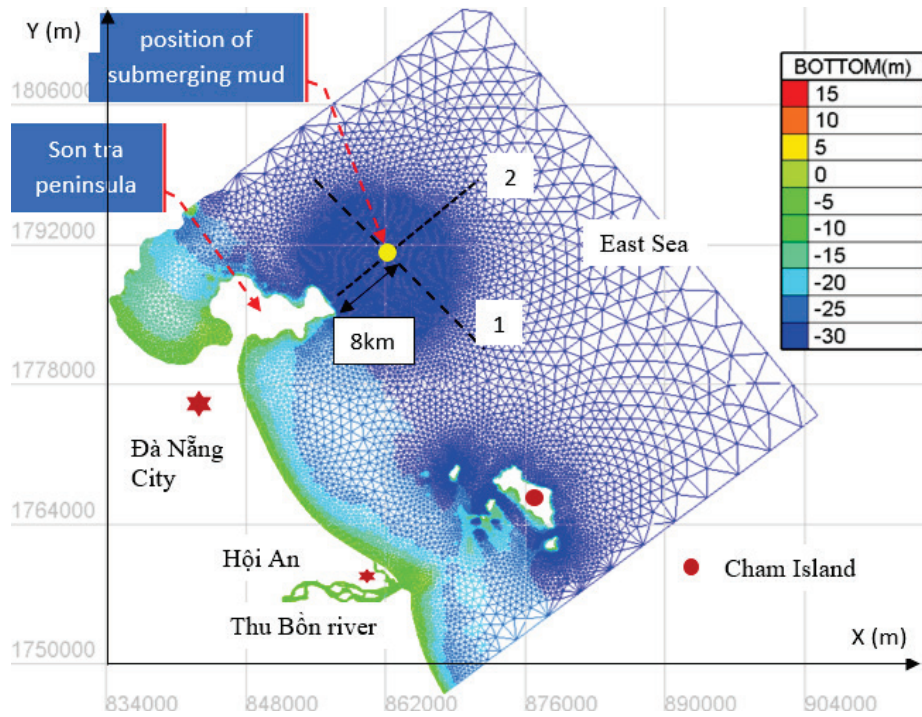


Figure 2 Numerical mesh with bathymetry in the study area.

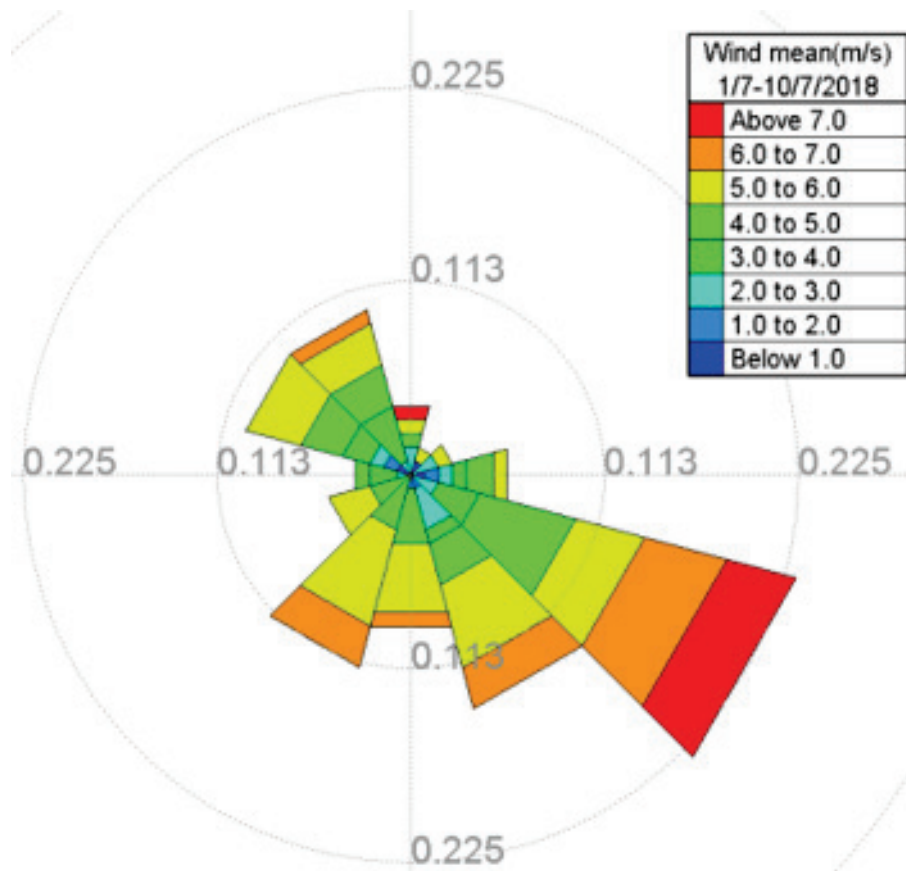


Figure 3 Typical wind rose in July 2018.

## 2.2 Numerical model

The numerical model of the study area is represented by 40,573 meshes. The biggest element size is 4,000 m (offshore elements), while the smallest is 50 m for meshes within the Thu-Bon River (see Figure 2). A three-dimensional element, composed of prisms subdivided into tetrahedrons, is generated by TELEMAC-3D from the two-dimensional element. The traditional sigma conversion is applied, producing an identical allocation of five vertical degrees to examine the vertical distribution of submerged sludge concentration over time and space. The area anticipated to accumulate submerged sludge features a non-structural grid with an average side length of 200 m.

The 3D hydrodynamics module solves the three-dimensional Navier-Stokes equations presented as follows:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \Delta(U) + F_x \quad (2)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \Delta(V) + F_y \quad (3)$$

$$\frac{\partial W}{\partial t} + U \frac{\partial W}{\partial x} + V \frac{\partial W}{\partial y} + W \frac{\partial W}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g + \nu \Delta(W) + F_z \quad (4)$$

$$p = p_{atm} + \rho_0 g (Z_s - z) + \rho_0 g \int_z^{Z_f} \frac{\Delta \rho}{\rho_0} dz + p_d \quad (5)$$

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} + V \frac{\partial C}{\partial y} + W \frac{\partial C}{\partial z} = Div[\nu Grad(T)] + Q \quad (6)$$

Where:

$U, V, W$  = velocity component in  $x, y, z$  directions,

$\rho$  = fluid density,

$p$  = pressure,

$p_{atm}$  = atmospheric pressure,

$\rho_0$  = reference density,

$g$  = gravitational acceleration,

$Z_s$  = free surface elevation,

$Z_f$  = bottom elevation,

$p_d$  = dynamic pressure,

$\nu$  = kinematic viscosity,

$F_x, F_y, F_z$  = external forces in  $x, y, z$  directions,

- C = suspended sediment concentration,
- T = temperature, and
- Q = source/sink of sediment.

The TOMAWAC module has been applied in the calculation of wave propagation. The governed equation of wave action is shown as follows:

$$\frac{\partial N}{\partial t} + \frac{\partial(\dot{x}N)}{\partial x} + \frac{\partial(\dot{y}N)}{\partial y} + \frac{\partial(\dot{k}_x N)}{\partial x} + \frac{\partial(\dot{k}_y N)}{\partial y} = Q(k_x, k_y, x, y, t) \quad (7)$$

Where:

- N = directional spectrum of wave action density,
- t = time,
- $k_x, k_y$  = wave number components in x, y directions,
- Q = source and sink terms.
- $\dot{x}, \dot{y}$  = position vector in the Cartesian coordinate system, and
- $\dot{k}_x, \dot{k}_y$  = vector indicating wave index.

The spatial-temporal variations of wave and wind data during the simulation period are taken from NOAA's database (NOAA 2022). The value of the wave varies between 1.5 m and 2.5 m and declines to around 1.0 m in the estuary regions thanks to the effect of Cu Lao Cham Island.

Typical wave height in the offshore area ranges from 1.5 m to 2.5 m and gradually decreases to about 1 m in the estuary area.

The research process uses following steps:

1. Model setup, which includes mesh generation and the implementation of boundary conditions;
2. Model calibration and validation using observation data; and
3. Study of the movement of submerged mud.

The parameters of the model include as follows: topography data, flow of Thu Bon river, wave parameters, wind, and Manning's roughness coefficient. Among these parameters, the roughness coefficient will be modified after the calibration and validation of observation data. The parameters of the model include the computational steps which were discussed in detail in our previous research (Nguyen et al. 2023).

The sediment transport simulation within the study area assumes that the sediment comprises non-cohesive materials. It is further presumed that the bed sediment

distribution is uniform across the entire region. The typical composition of riverbed sand includes representative grain sizes of 0.1 mm, 0.5 mm, 0.8 mm, and 1.5 mm, with respective proportions of 4%, 65%, 26%, and 5%.

### 3. SIMULATION OF SEWAGE SLUDGE DISPERSION IN THE COASTAL AREA OF DA-NANG

#### 3.1 Calibration and validation

The hydrodynamic model was calibrated and verified according to observation data at Son Tra hydrographic station, and wave correction at two locations: s1 and w1 (refer to Figure 4).

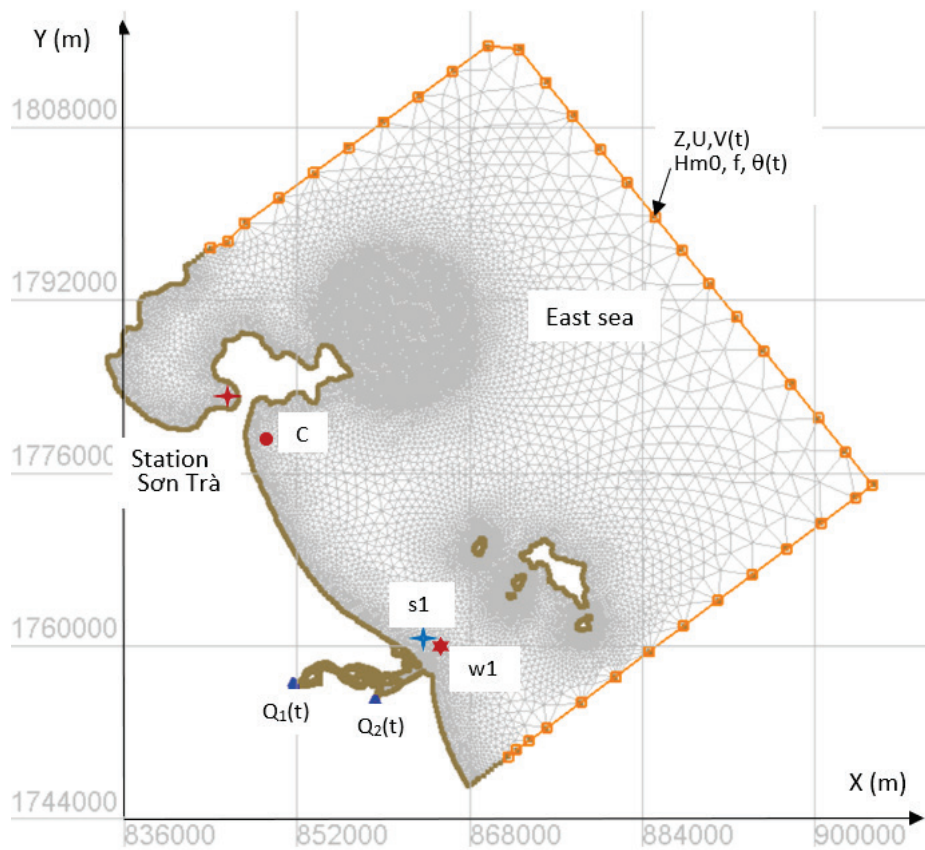


Figure 4 Boundary conditions of the study area.

## Calibration

The numerical model was calibrated using 8-day data from January 5–13, 2019. Graphs and analysis results are presented in Figure 5.

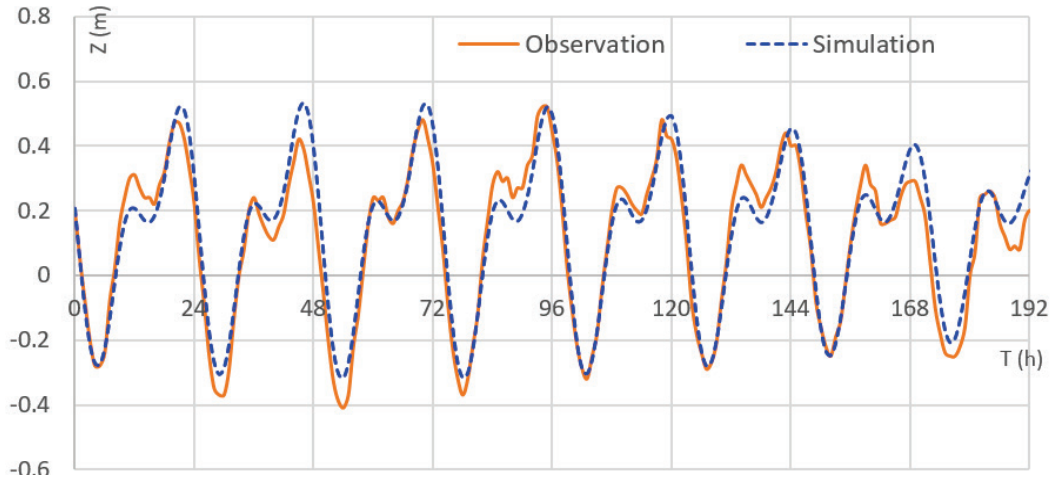


Figure 5 Comparison of water level  $z$  between simulation and observation data.

To evaluate the agreement between simulation and observation results, some evaluation criteria and harmonic analysis of the two-time series are summarized in the following table. With a Nash-Sutcliffe Efficiency (NSE) of 0.9 and a Root Mean Square Error (RMSE) of 0.0005, the simulation demonstrates a high level of agreement with the observed data, indicating reliable model performance. Table 1 summarizes the assessment of the agreement between simulated and observed mean, maximum, and minimum water levels.

Table 1 Comparison results of simulated and observed water levels.

Value	Observation (m)	Simulation (m)
Medium	0.106	0.110
Maximum	0.520	0.530
Minimum	-0.410	-0.320

## Validation

The numerical model was validated at Son Tra Marine station from April 12–18, 2019. Graphs and analysis results are presented in Figure 6:

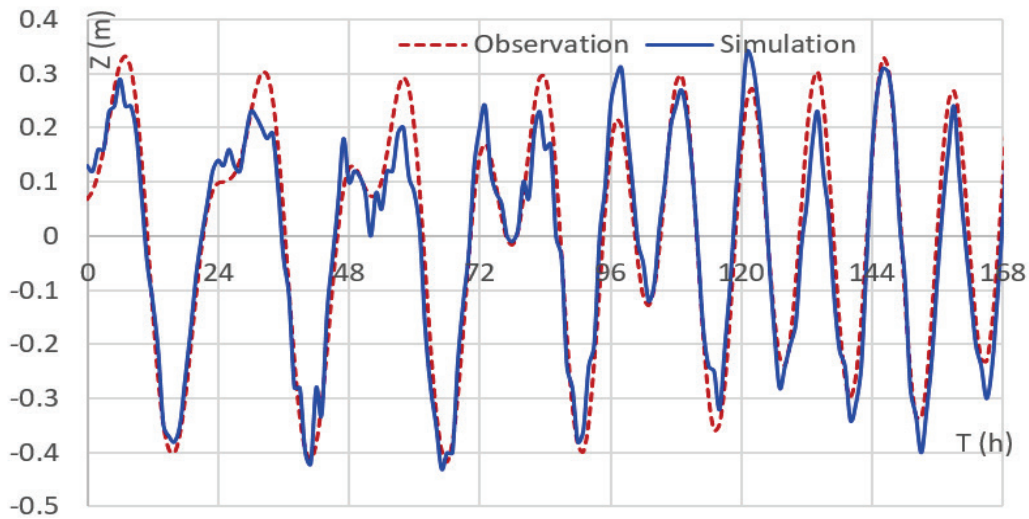


Figure 6 Comparison of water level  $z$  using simulation and observation data.

With a Nash-Sutcliffe Efficiency (NSE) of 0.918 and a Root Mean Square Error (RMSE) of 0.059, along with comparative metrics presented in the following table, the simulation can be considered to reliably reflect the observed values. Table 2 presents a comparison of simulated and observed mean, maximum, and minimum water levels.

Table 2 Comparison results of simulated and observed water levels.

Value	Observation	Simulation
Mean	-0.01	0.00
Maximum	0.34	0.33
Minimum	-0.43	-0.42

### Calibration of a wave model

The wave model has been calibrated with observation data from October 16–November 12, 2014. Graphs and analysis results are presented in Figures 7 and 8:

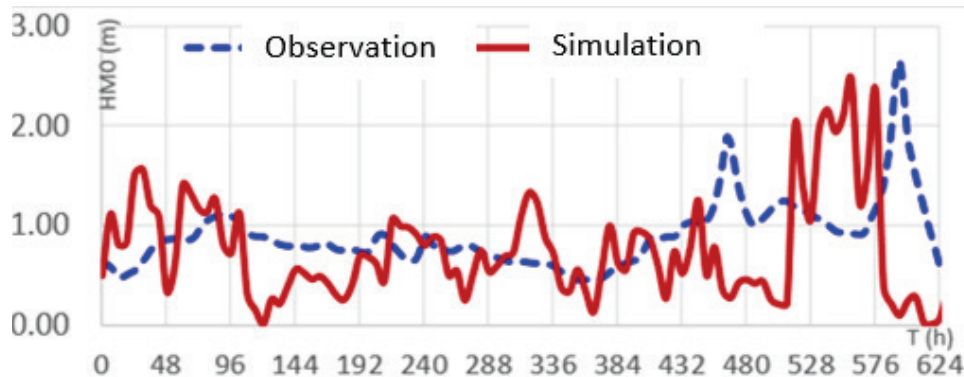


Figure 7 Height of wave  $HM_0$  at location  $s_1$  from October 16–November 12, 2014.

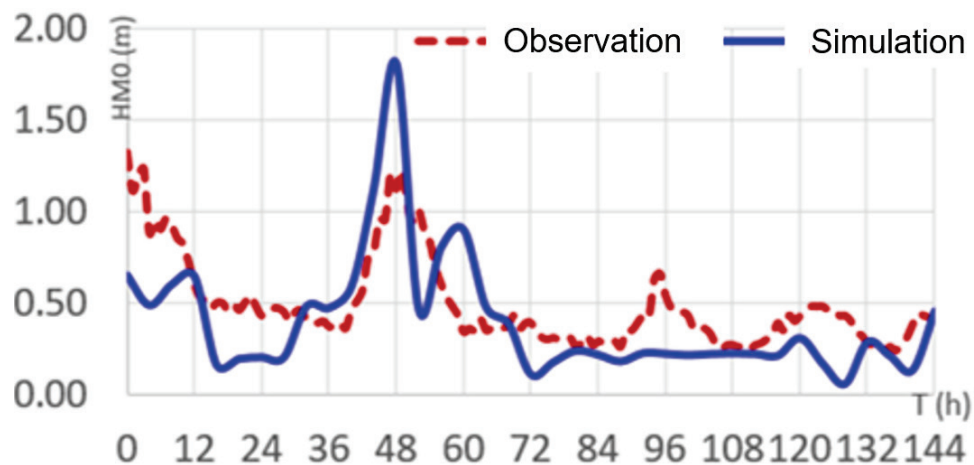


Figure 8 Height of wave HMO at location w1 from October 19–25, 2016.

The calibration and validation results show that the hydraulic and wave model is reliable and employed for simulation and running the different scenarios.

#### Calibration of a sediment model

The sediment model has been calibrated by employing measurement data, and the simulation results tend to underestimate compared to the observed values. This discrepancy may be attributed to several potential factors: the geological data used in the model may not accurately reflect actual conditions; the numerical model employed for sediment transport simulation is of a hybrid type that may not be entirely suitable; and measurement errors in sediment data may have occurred due to the complex conditions of coastal sampling, which involve various risk factors affecting sampling techniques. The underestimation in the sediment transport simulation could potentially lead to reduced computed values of sediment deposition and scour along the riverbed. The calibration results of the sediment transport model indicate a certain level of reliability, suggesting that the model can be applied in studies of sediment transport. These results are presented in Figure 9:

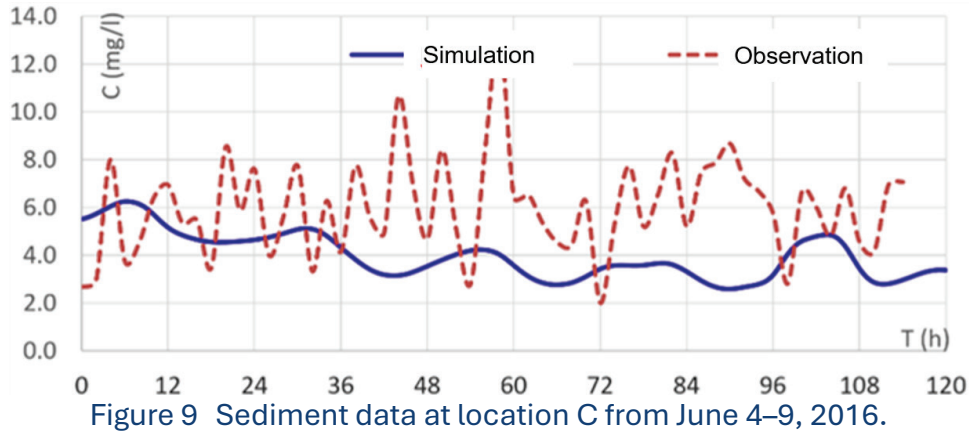


Figure 9 Sediment data at location C from June 4–9, 2016.

### 3.2 Scenarios

To evaluate the impact of the average tidal current on the dispersion of sludge in the study area, a simulation was performed employing assumed circumstances. This scenario involved the submergence of an amount of 3,300 m<sup>3</sup>/day for three hours daily at a position around 8 km from the Son Tra peninsula (refer to Figure 2). Simulations were conducted for the first 10-day periods of January, March, May, and July 2018. The discharge occurred at a depth of 3 m above sea level. The typical discharge intensity from simulation results is depicted in Figure 10, showing the sludge concentration at the surface at the submersion site, which demonstrates rapid dilution following submersion at the specified location.

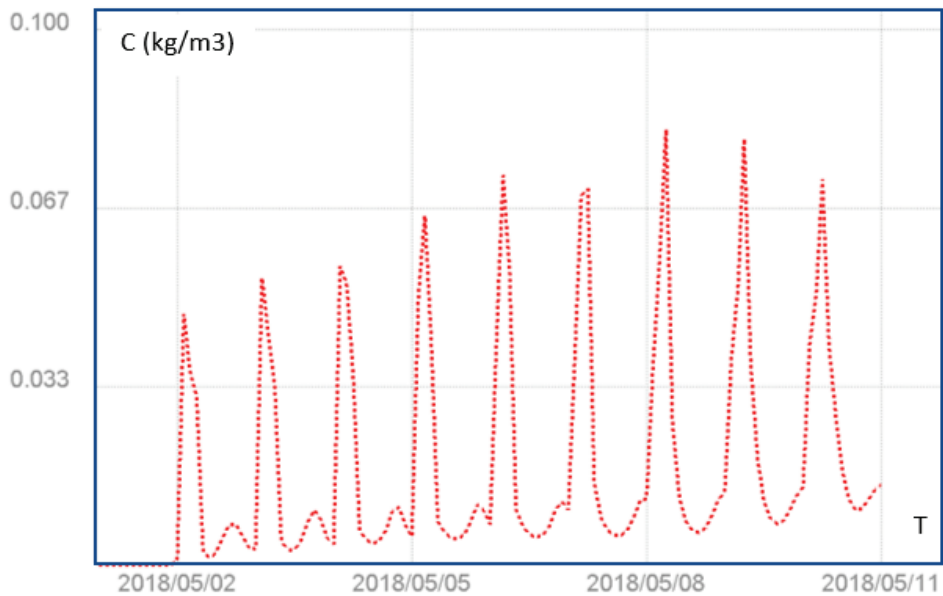


Figure 10 Suspended sludge concentration at the sludge submersion position (simulation results).

### 3.3 Typical results

**Average tidal current:** The analysis of the average tidal currents over the four different simulation periods reveals variations in both strength and velocity direction. Notably, the average tidal current directed toward the southeast during the period from January 1 to January 10, 2018, is relatively the strongest (see Figure 11). These differences result in varying degrees of horizontal sludge diffusion.

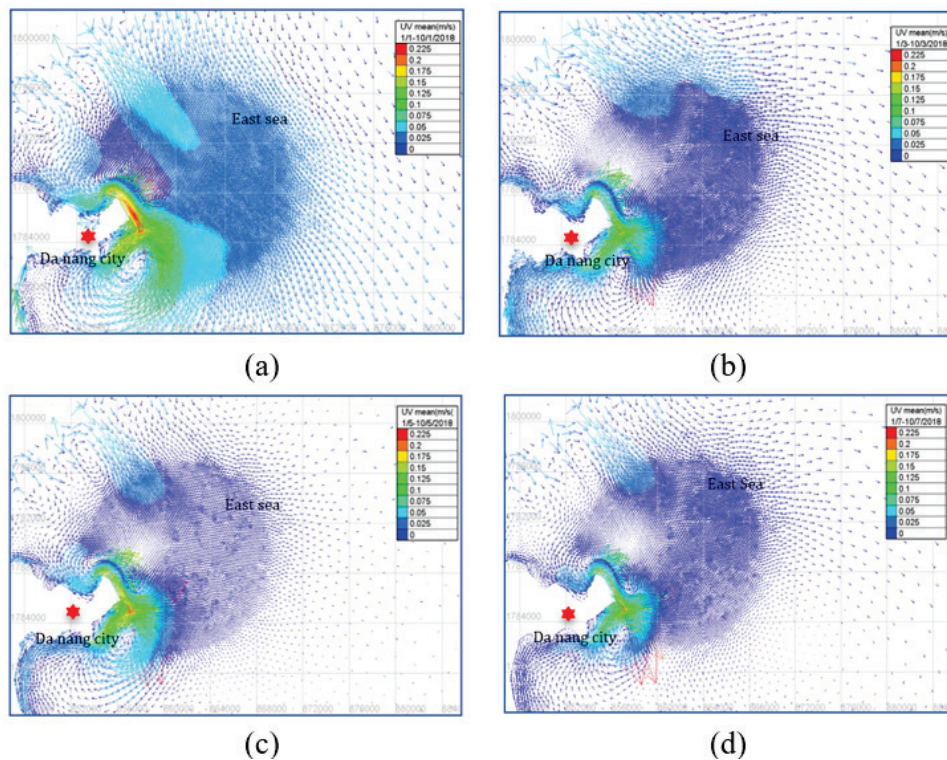


Figure 11 Average tidal current for the first 10-day periods of (a) January, (b) March, (c) May, and (d) July 2018.

**Horizontal sludge dispersion:** Figure 12 illustrates the vertically averaged sludge distribution at selected times after submersion. The simulation results demonstrate the impact of sludge convection and diffusion over space and time. Due to the effect of tidal currents, significant fluctuations occur in the high-concentration sand and sludge areas, predominantly in the northwest-southeast direction in the simulation duration. The results align with those showing the strongest tidal current in Figure 11.

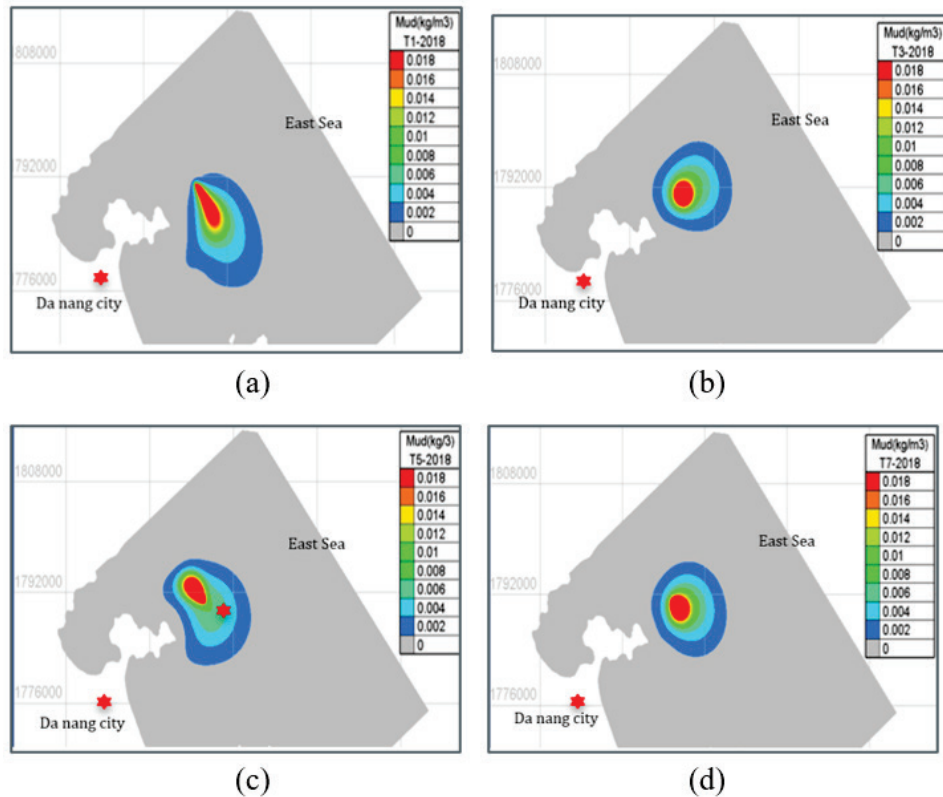


Figure 12 Average concentration of suspended sludge after 3 hours of submersion in the fifth days of (a) January, (b) March, (c) May, and (d) July 2018.

Due to the combined effects of convection and diffusion, the simulation results indicate that a sludge concentration area of 1 mg/L can extend up to 20 km offshore in the southeast direction from the submersion site.

**Vertical sludge dispersion:** The vertical distributions of sewage sludge at cross-sections 1-1 and 2-2 for various scenarios are presented in Figure 13. The simulation results for cross-section 1-1 indicate that the spread of sewage sludge tends to follow a northwest-southeast direction. Additionally, the results reveal the phenomenon of sludge sedimentation near the water surface following discharge. Figure 14 presents the simulation results illustrating the vertical distribution of sludge concentration on the fifth day of March, May, and July 2018, respectively.

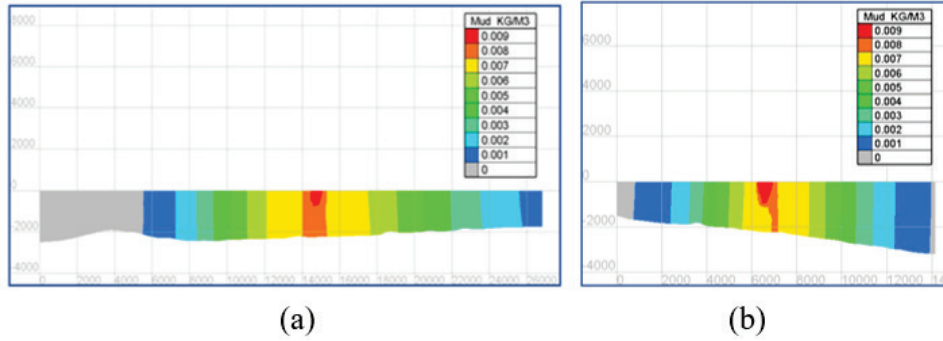


Figure 13 Simulated sludge concentration distribution in the vertical direction in January 5, 2018, at cross-section 1-1 (a); and at cross-section 2-2 (b).

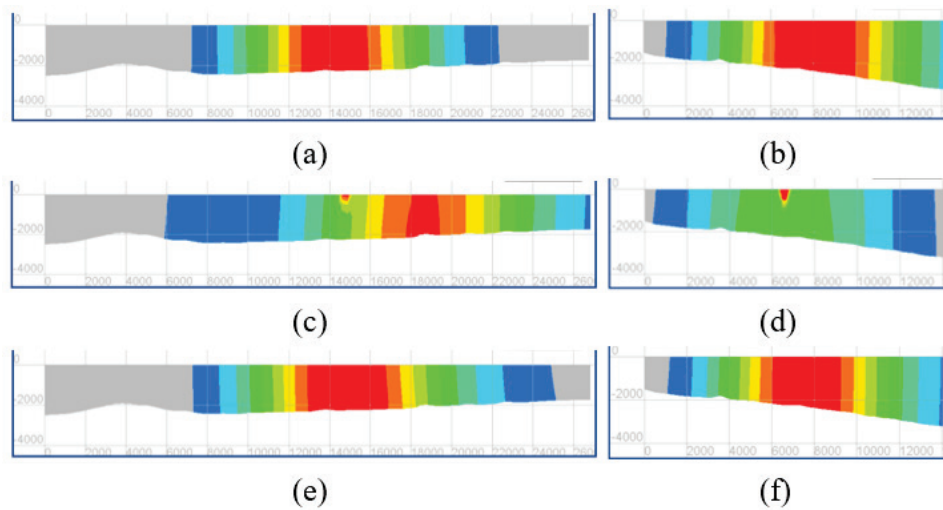


Figure 14 Simulated sludge concentration distribution in the vertical direction respectively in the fifth days of March, May, and July 2018 at cross-section 1-1 (left), and 2-2 (right).

**Seabed evolution:** To quantitatively evaluate the influence of the average tidal current on sludge deposition to the seabed, the bottom variations for different discharge period scenarios are presented in Figure 15. The graph indicates that sludge deposition to the seabed varies depending on the timing of the sludge submersion. During the first 10 days of January 2018, sludge accretion tends to migrate southeast. The average transport patterns for the first 10 days of March and July are similar. Notably, the discharge scenario from May 1–18 shows a spreading trend closer to the Son Tra peninsula compared to the other submersion scenarios.

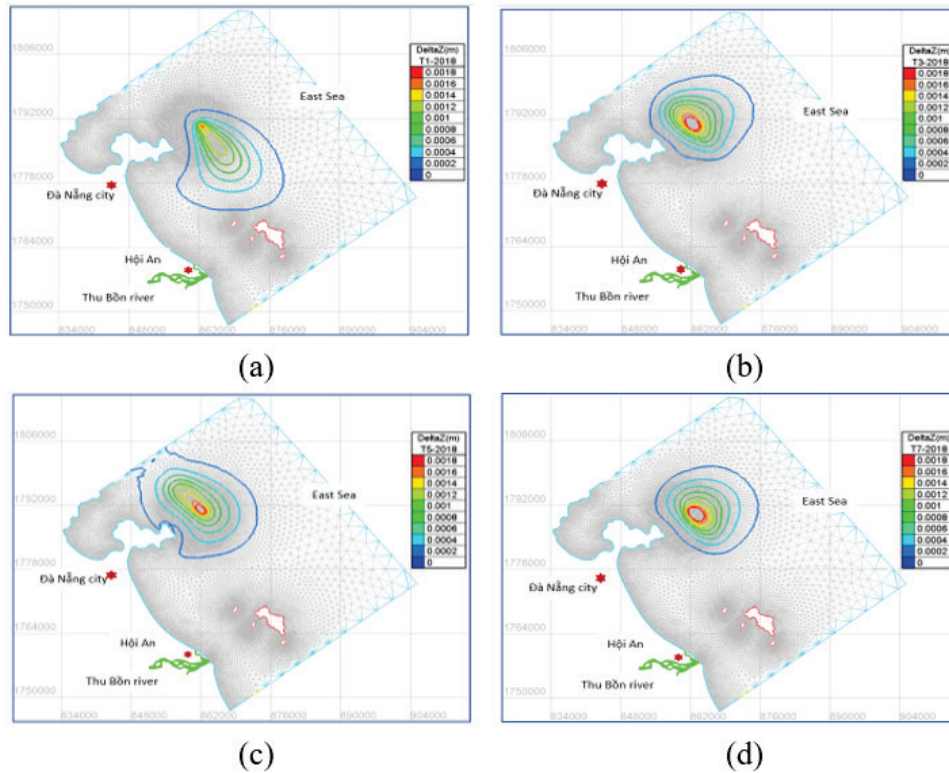


Figure 15 Increasing seabed elevation after the first 10-day periods of (a) January, (b) March, (c) May, and (d) July 2018.

The model incorporates random waves characterized by three parameters: intensity ( $Hm0$ ), period ( $T$ ), and wave direction ( $\theta$ ), derived from NOAA's global model (NOAA 2022). The downscaling models from the global data of NOAA have been developed to obtain the wave parameters for the research area. The minimum frequency considered for these waves is 0.07, with 15 waves selected at a frequency increment of approximately 1.1. The simulation includes 16 wave directions, encompassing the entire 360° plane. Across all simulated scenarios, the wave direction at the discharge point consistently trends shoreward, with wave angles ranging from 200° to 290°. This observation is consistent with the general behavior of waves becoming perpendicular to the shore as it is approached (refer to Figure 16). However, variations in wave intensity and period (see Figure 17, comparing May and July) result in differing sludge dispersion patterns. The significantly higher wave intensity in May leads to a pronounced presence of sludge in the coastal area, as evidenced by the images of sludge concentration (Figure 14) and bottom elevation (Figure 15).

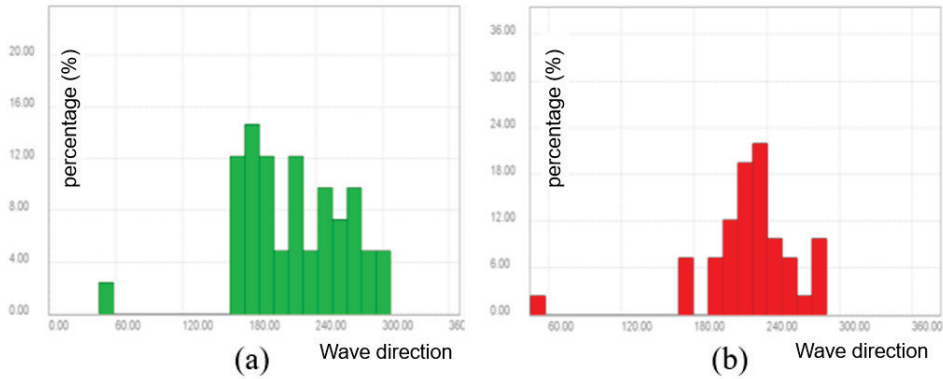


Figure 16 Wave direction distribution at the sludge discharge point in (a) May, and (b) July.  
 NOTE: North is conventionally set at 0 degrees.

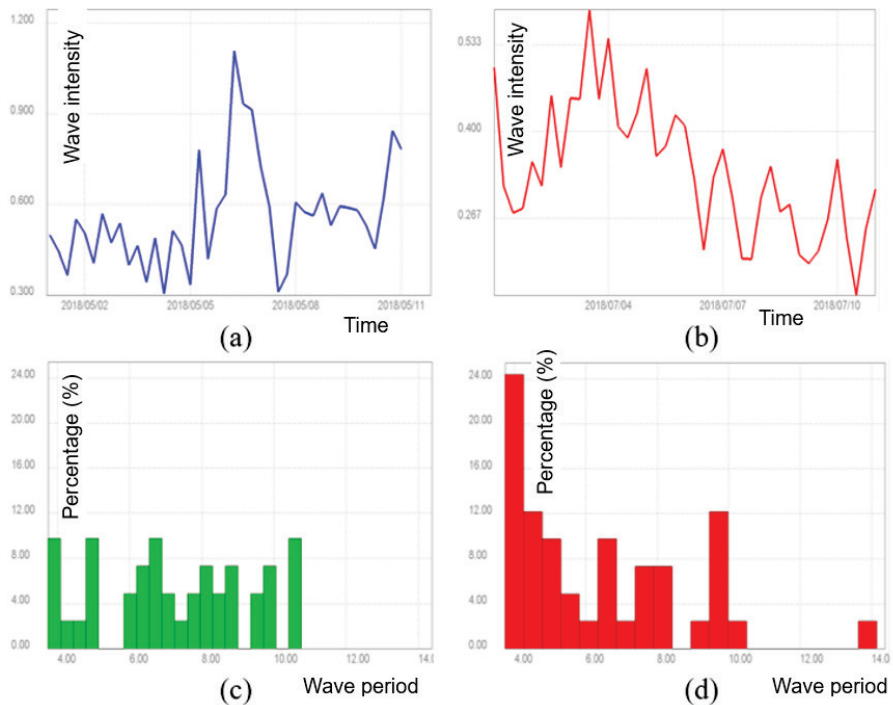


Figure 17 Comparison of wave intensity (a and b) and wave period (c and d) for May and July 2018, respectively.

#### 4. CONCLUSION

Based on the simulation results applied to the above scenarios, several observations can be made. The distribution of underwater mud concentration at a position around 8 km seaward of the Son Tra peninsula is primarily influenced by two factors: convection (due to tidal currents) and diffusion (dilution). The concentration of discharged sludge rapidly

dilutes with the adjacent area due to the influence of diffusion. This result is preliminary and may be refined with the collection of observation information. Overall, the parameters assumed in this study indicate a tendency for sludge to be transported offshore, away from the Son Tra peninsula. During the periods of March and July 2018, sludge tends to be pushed further offshore compared to the other two simulation periods. This finding is significant when selecting discharge periods to minimize the risk of sludge spreading toward the coast. Among the discharge scenarios, the plan from May 1–10, 2018, yields the worst results in terms of sludge spread toward the shore. Additionally, the simulation results show that during the discharge periods from March 1–10, 2018, and July 1–10, 2018, the sludge tends to be transported farther offshore compared to the other two simulated scenarios. The discharge periods are designed to minimize the risk of sludge dispersion toward the coastline, thereby reducing the pollution impact. It is recommended to conduct field data collection on waves, sediment, and flow conditions to provide a more robust dataset for model calibration and validation, thereby enhancing the accuracy of simulation results.

## ACKNOWLEDGMENTS

This research is funded by Vietnam National University HoChiMinh City (VNU-HCM) under grant number C2024-20-29.

The study was conducted at Ho Chi Minh City University of Technology and the High-Performance Computing Center (HPCC).

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