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Assessment of Hydrodynamic Changes Induced by Dredging and Sand Mining in Tra Ly Estuary for Sustainable Resource Management

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ABSTRACT

The combined effects of dredging and sand mining in estuarine systems remain insufficiently quantified, despite their widespread application for both navigation improvement and material extraction. This study investigates hydrodynamic responses to dredging coupled with sand extraction in the Tra Ly estuary, northern Vietnam, using a coupled MIKE21 modeling system. The model integrates hydrodynamic and wave modules and is calibrated against field observations to ensure reliable simulation of water levels, flow velocity, and tidal dynamics. Two scenarios were simulated, representing pre- and post-intervention bathymetric conditions under identical boundary forcing. Results show that channel deepening leads to a reduction in flow velocity within the range of 0.1–0.6 m/s, accompanied by a decrease in upstream water levels of up to 0.08 m and an increase in tidal discharge reaching 400–600 m³/s. These findings indicate that dredging combined with sand mining enhances channel conveyance while only moderately altering the hydrodynamic regime. Although the impacts remain limited under normal conditions, changes in flow structure may influence sediment transport and system behavior under extreme events. The results provide quantitative evidence for evaluating combined dredging–mining impacts and support sustainable management of estuarine systems.

Keywords: *Hydrodynamics; sand mining; MIKE21; Tidal dynamics; Channel deepening.*

1. Introduction

Estuaries are highly dynamic transitional environments where fluvial and marine processes interact to control hydrodynamics, sediment transport, and morphological evolution. These systems are governed by the combined effects of river discharge, tidal forcing, wave action, and sediment dynamics, which regulate energy distribution and material fluxes across the land–sea interface (Dalrymple et al., 2012; Ma et al., 2010). Recent studies further emphasize that estuarine responses to external forcing are increasingly influenced by human interventions, particularly under conditions of intensified resource exploitation and climate variability (Dunn et al., 2023; Wang, 2024).

Among anthropogenic activities, dredging and sand mining are widely implemented to maintain navigation channels and supply construction materials. In many estuaries, these activities are conducted simultaneously, leading to coupled alterations in channel morphology and sediment budgets. However, such combined interventions may disturb the hydrodynamic equilibrium by modifying flow structure, tidal asymmetry, and sediment transport pathways (Cox et al., 2022; Jia et al., 2024; Tran et al., 2022). Recent studies indicate that channel deepening associated with sand extraction can reduce flow resistance, redistribute hydrodynamic energy, and alter current velocity and water level gradients (Bendô et al., 2023; Winterwerp & Wang, 2021). In addition, increased water depth may enhance wave propagation

toward nearshore zones, potentially intensifying coastal erosion and affecting shoreline stability, particularly under extreme conditions such as storms and floods (Sohrt et al., 2021; Yang et al., 2019).

Numerical modeling has become an essential tool for investigating hydrodynamic processes and quantifying the impacts of human-induced changes in estuarine environments. Process-based models, such as the MIKE21 system developed by the Danish Hydraulic Institute, enable the simulation of depth-averaged flow, wave dynamics, and sediment transport within a coupled framework. The hydrodynamic module is based on the shallow water equations and is solved using a finite-volume approach on an unstructured mesh, allowing accurate representation of complex coastal and estuarine geometries (Xu et al., 2023; Yan et al., 2022).

The integration of hydrodynamic (HD) and spectral wave (SW) modules allows for explicit representation of wave–current interactions through radiation stress gradients, which are essential for understanding energy transfer and sediment mobility in shallow environments (Warren & Bach, 1992). Such coupled modeling approaches have been widely applied in recent studies to assess hydrodynamic responses and sediment transport under dredging and coastal engineering interventions (Ngo & Nguyen, 2023).

The Tra Ly estuary in northern Vietnam is a tide-dominated system characterized by strong interactions between river discharge and marine forcing. The area plays a key role in inland waterway transportation and regional development. A dredging project combined with sand mining has been proposed to improve navigation and provide construction materials. While these activities bring economic benefits, their combined hydrodynamic impacts remain insufficiently quantified, particularly in terms of flow velocity, water level variation, and tidal exchange.

This study aims to assess hydrodynamic changes induced by dredging and sand mining in the Tra Ly estuary using a coupled MIKE21 model. The model is calibrated and validated against field observations to ensure reliable representation of key hydrodynamic variables. The objectives are to: (i) quantify changes in flow velocity and tidal dynamics; (ii) evaluate variations in water levels and tidal discharge; and (iii) discuss implications for sustainable resource management. The results provide a quantitative basis for understanding the combined effects of dredging and sand mining and support evidence-based decision-making in estuarine systems.

2. Material and methods

2.1. Case study

The study focuses on the Tra Ly estuary located in Thai Binh Province, northern Vietnam, which is a typical tide-dominated river mouth influenced by both fluvial discharge and marine processes. The estuary plays an important role in inland waterway transportation and sediment exchange between the Red River system and the coastal zone.



Figure 1. Boundary of the proposed dredging and sand mining area at the Tra Ly estuary.

The investigated area extends from the upstream river section to the nearshore coastal zone, covering approximately 4.6 km along the navigation channel and extending offshore to capture wave–current interactions (Figure 1). The bathymetry is characterized by a gently sloping riverbed transitioning into a shallow coastal shelf, where tidal dynamics and wave action strongly influence flow patterns.

2.2. Hydrodynamic modeling

Hydrodynamic processes were simulated using the MIKE21 FM system developed by the Danish Hydraulic Institute. The model solves the depth-integrated two-dimensional shallow water equations on an unstructured mesh using a finite-volume approach. A coupled configuration between the hydrodynamic (HD) and spectral wave (SW) modules was applied to account for wave–current interactions, while sediment-related outputs were used for interpretation.

The HD module solves the depth-integrated shallow water equations, including the continuity equation (DHI, 2009):

$$\frac{\partial h}{\partial t} + \frac{\partial hU}{\partial x} + \frac{\partial hV}{\partial y} = hS \quad (1)$$

Where U and V are the depth-averaged velocity components corresponding to the velocity components u and v in the x and y directions, defined as follows:

$$U = \frac{1}{h} \int_{-d}^{\eta} u dz, \quad V = \frac{1}{h} \int_{-d}^{\eta} v dz \quad (2)$$

Where $h = \eta + d$ is the total water depth, defined as the sum of the water surface elevation (η) and the bed depth (d).

And the momentum equations as following (DHI, 2009):

$$\begin{aligned} \frac{\partial hU}{\partial t} + \frac{\partial hU^2}{\partial x} + \frac{\partial hUV}{\partial y} = fVh - gh \frac{\partial \eta}{\partial x} - \frac{h}{\rho_0} \frac{\partial p_a}{\partial x} - \frac{gh^2}{2\rho_0} \frac{\partial \rho}{\partial x} + \\ \frac{\tau_{sx}}{\rho_0} - \frac{\tau_{bx}}{\rho_0} - \frac{1}{\rho_0} \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial x} \right) + \frac{\partial}{\partial x} (hT_{xx}) + \frac{\partial}{\partial y} (hT_{xy}) + hU_s S \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial hV}{\partial t} + \frac{\partial hV^2}{\partial x} + \frac{\partial hUV}{\partial y} = fUh - gh \frac{\partial \eta}{\partial y} - \frac{h}{\rho_0} \frac{\partial p_a}{\partial y} - \frac{gh^2}{2\rho_0} \frac{\partial \rho}{\partial y} + \\ \frac{\tau_{sy}}{\rho_0} - \frac{\tau_{by}}{\rho_0} - \frac{1}{\rho_0} \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial x} \right) + \frac{\partial}{\partial x} (hT_{xy}) + \frac{\partial}{\partial y} (hT_{yy}) + hV_s S \end{aligned} \quad (4)$$

The terms T_{xx} , T_{yy} and T_{xy} represent the components of the total viscous stresses, which are calculated based on the horizontal velocity gradients.

The spectral wave module (SW) is based on the wave action conservation equation and simulates wave generation, propagation, and dissipation processes, including wind input, whitecapping, bottom friction, and depth-induced breaking. The coupling between HD and SW allows the model to account for wave–current interactions through radiation stress gradients.

The computational domain was discretized using an unstructured mesh with approximately 30,000 elements. Grid resolution ranges from 10–50 m in the navigation channel and nearshore areas to 300–500 m offshore, allowing accurate representation of bathymetry and shoreline geometry.

2.3. Data and boundary conditions

The model integrates multiple data sources. Bathymetry was constructed from project surveys at a scale of 1:5,000 combined with regional datasets ranging from 1:10,000 to 1:50,000. Offshore wave and wind conditions were derived from the ERA5 reanalysis dataset, while river discharge and upstream water levels were used to represent fluvial forcing. Tidal forcing was obtained from the global tidal toolbox integrated within MIKE21.

The computational domain includes three open sea boundaries located in the northeast, east, and southwest, and one upstream river boundary. Along the sea boundaries, spatially and temporally varying water levels and wave parameters were prescribed, whereas river boundaries were assigned discharge and water level conditions.

A constant time step of 30 s was applied with a Courant–Friedrichs–Lewy (CFL) number of 0.8 to ensure numerical stability. Additional hydraulic settings include a Smagorinsky eddy viscosity formulation with a coefficient of 0.28, a drying depth of 0.005 m, a flooding depth of 0.05 m, and a wetting depth of 0.1 m.

2.4. Model calibration and validation

Model calibration was performed by adjusting bed roughness coefficients. Manning values were assigned in the range of 28–35 m/s, varying by bathymetric zone. Calibration was based on comparison between simulated and observed data, including water levels, wave characteristics, flow velocity, and suspended sediment concentration.

The Nash–Sutcliffe efficiency coefficient is used to evaluate model performance, where values closer to 1 indicate higher agreement between observed and simulated data.

$$\text{Nash} = 1 - \frac{\sum (X_{o,i} - X_{s,i})^2}{\sum (X_{o,i} - \bar{X}_o)^2} \quad (5)$$

Where $X_{o,i}$ is the observed value, $X_{s,i}$ is the simulated value, and $\bar{X}_o$ is the mean of observed values.

The Nash value close to 1 indicates a strong agreement between observed and simulated water levels.

2.5. Scenario design

Two scenarios were simulated to assess the impacts of dredging and sand mining. The baseline scenario represents existing bathymetry, while the intervention scenario reflects channel deepening to approximately 7.8 m. Both scenarios were run under identical boundaries and forcing conditions to isolate the effects of bathymetric modification.

The analysis focuses on three key indicators: flow velocity, water level variation, and tidal discharge. Simulations were conducted under northeast and southwest monsoon conditions, as well as representative extreme events, including storm and flood scenarios. This approach allows direct comparison of hydrodynamic responses before and after dredging.

3. Results and Discussion

Prior to scenario analysis, model performance was evaluated to ensure reliability. The model reproduced observed water levels with high accuracy (Nash $\approx$ 0.97) and showed acceptable agreement for wave and flow parameters, providing a reliable basis for subsequent hydrodynamic analysis.

3.1 Hydrodynamic changes

Dredging combined with sand mining results in a consistent but moderate reduction in

flow velocity across the study area. Depth-averaged velocities generally range from 0.1 to 0.6 m/s under existing conditions and decrease slightly after channel deepening, with mean reductions of approximately 0.01–0.04 m/s depending on location (Table 1 and Table 2).

Spatial patterns of flow are clearly modified, as shown in Figure 2. Under northeast monsoon conditions, flow fields become more uniform after dredging, with reduced lateral variability and stronger alignment along the main channel axis. This effect is observed during both flood and ebb tides, indicating a systematic reorganization of the flow structure rather than localized changes.

Figure 3 presents the schematic distribution of sampling locations (P1–P8) used for data extraction and quantitative analysis, forming the basis for evaluating changes in flow velocity, water level, and tidal discharge between baseline and dredged scenarios.

Temporal variations further confirm these trends. As illustrated in Figure 4, flow velocity and direction exhibit reduced fluctuations after dredging, particularly during peak tidal phases. The main current becomes more stable and concentrated, while directional variability decreases. These changes indicate reduced turbulence and more efficient flow conveyance within the channel.

Overall, the results demonstrate that dredging primarily affects flow distribution and stability, rather than significantly altering the magnitude of velocity.

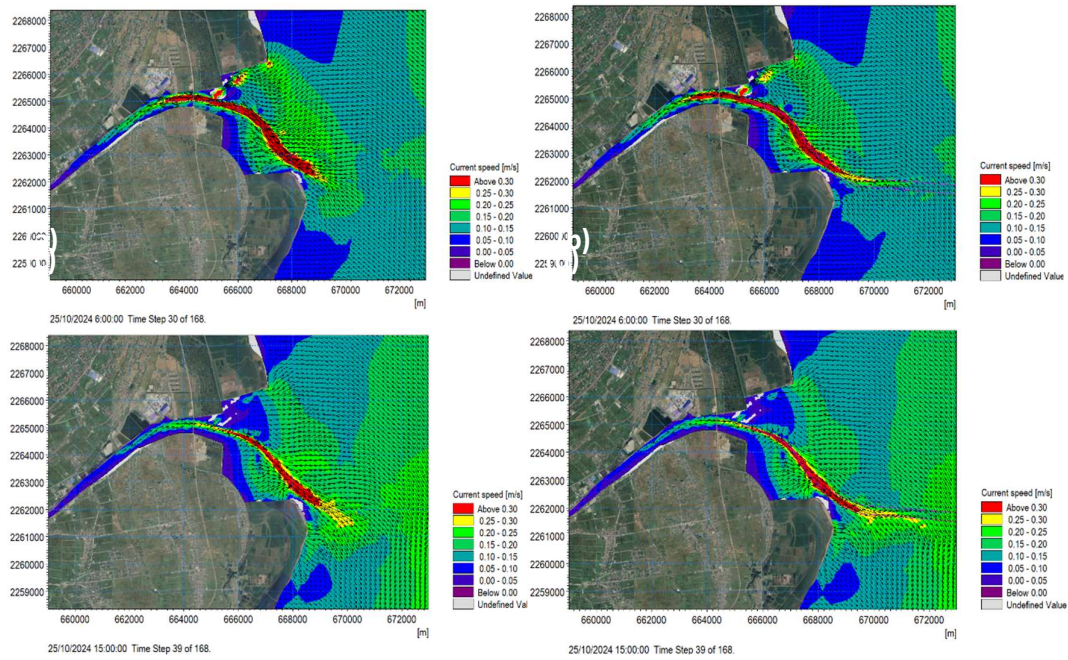


Figure 2. Flow velocity fields under northeast monsoon conditions: (a) flood tide and (b) ebb tide for existing bathymetry; (c) flood tide and (d) ebb tide for dredged bathymetry (-1 m).

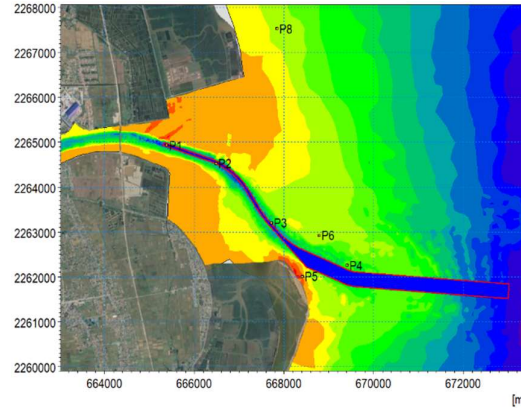


Figure 3. Schematic map showing sampling locations (P1–P8) used for data extraction and hydrodynamic assessment.

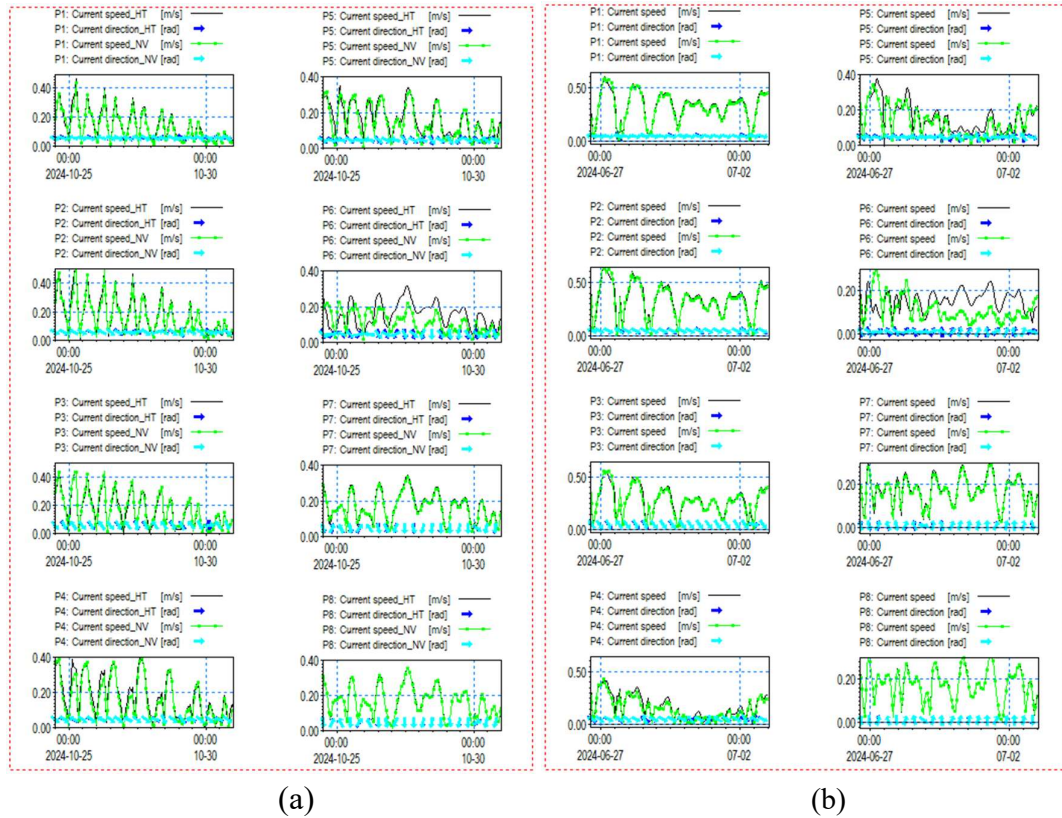


Figure 4. Comparison of flow velocity and direction before and after dredging (−1 m): (a) northeast monsoon and (b) southwest monsoon conditions.

3.2. Water level changes

Changes in water level are relatively small but spatially systematic. Under northeast monsoon conditions, tidal water levels range from approximately -1.6 m to $+1.8$ m, with a maximum reduction of about **0.08 m** observed in upstream sections after dredging (Table 1).

The magnitude of water level changes decreases gradually from upstream to the estuary mouth, indicating that dredging impacts are more pronounced in confined river sections. In most locations, mean water level differences remain within **0.00–0.01 m**, confirming that the overall tidal range is largely preserved.

A similar pattern is observed under southwest monsoon conditions (Table 2), although slightly larger variations occur at some locations due to combined river discharge and tidal forcing. Despite these variations, the overall change remains limited.

These results indicate that dredging induces a minor lowering of water levels without significantly modifying tidal dynamics, and its influence is primarily local rather than system wide.

Table 1. Variation of hydrodynamic parameters after dredging under northeast monsoon conditions.

Parameter	Location	Existing condition			Dredged condition			Difference (Existing – Dredged)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Velocity (m/s)	P1	-1.53	1.61	0.00	-1.61	1.60	-0.01	0.08	0.00	0.01
	P2	-1.53	1.59	-0.01	-1.61	1.58	-0.01	0.08	0.01	0.01
	P3	-1.53	1.58	-0.01	-1.59	1.57	-0.01	0.06	0.00	0.01
	P4	-1.52	1.57	0.00	-1.56	1.56	-0.01	0.04	0.00	0.00
	P5	-1.51	1.57	0.00	-1.55	1.56	-0.01	0.04	0.00	0.00
	P6	-1.52	1.57	-0.01	-1.53	1.57	-0.01	0.01	0.00	0.00
	P7	-1.52	1.57	-0.01	-1.52	1.57	-0.01	0.00	0.00	0.00
	P8	-1.52	1.57	-0.01	-1.52	1.57	-0.01	0.00	0.00	0.00
Velocity (m/s)	P1	0.01	0.46	0.14	0.01	0.44	0.13	0.00	0.03	0.01
	P2	0.01	0.56	0.17	0.01	0.53	0.17	0.00	0.03	0.01
	P3	0.01	0.43	0.17	0.00	0.44	0.17	0.00	-0.01	0.00
	P4	0.00	0.40	0.18	0.00	0.39	0.16	0.00	0.01	0.02
	P5	0.02	0.35	0.16	0.00	0.32	0.15	0.01	0.03	0.02
	P6	0.02	0.32	0.15	0.02	0.23	0.12	0.00	0.09	0.04
	P7	0.03	0.35	0.17	0.02	0.33	0.16	0.00	0.01	0.00
	P8	0.01	0.36	0.17	0.01	0.35	0.16	0.00	0.00	0.00
Flow direction (°)	P1	74	307	181	62	309	178	12	-2	3
	P2	110	300	193	105	299	189	5	2	4
	P3	107	341	229	23	336	233	84	5	-4
	P4	121	306	186	123	308	188	-1	-2	-2
	P5	107	317	177	91	307	174	16	10	3
	P6	20	354	186	26	341	171	-5	13	15
	P7	2	359	185	1	360	186	1	-1	-1
	P8	2	357	182	1	359	183	1	-2	-1

Table 2. Variation of hydrodynamic parameters after dredging under southwest monsoon conditions.

Parameter	Location	Existing condition			Dredged condition			Difference (Existing – Dredged)		
		Min	Max	Mean	Min	Min	Max	Mean	Max	Min
Velocity (m/s)	P1	-1.22	1.80	0.08	-1.57	1.79	0.05	0.36	0.01	0.03
	P2	-1.25	1.77	0.06	-1.61	1.77	0.03	0.36	0.01	0.03
	P3	-1.27	1.76	0.04	-1.63	1.75	0.02	0.36	0.00	0.02
	P4	-1.29	1.75	0.03	-1.62	1.75	0.02	0.33	0.00	0.02
	P5	-1.31	1.75	0.03	-1.62	1.75	0.02	0.31	0.00	0.01
	P6	-1.60	1.75	0.02	-1.61	1.75	0.02	0.01	0.00	0.00
	P7	-1.60	1.76	0.02	-1.60	1.76	0.02	0.00	0.00	0.00
	P8	-1.60	1.76	0.02	-1.61	1.76	0.02	0.00	0.00	0.00

Parameter	Location	Existing condition			Dredged condition			Difference (Existing – Dredged)		
		Min	Max	Mean	Min	Min	Max	Mean	Max	Min
Velocity (m/s)	P1	0.01	0.60	0.32	0.02	0.58	0.31	-0.01	0.02	0.01
	P2	0.01	0.67	0.34	0.01	0.67	0.33	0.00	0.00	0.01
	P3	0.01	0.57	0.28	0.01	0.56	0.27	0.00	0.01	0.01
	P4	0.01	0.42	0.17	0.01	0.43	0.15	0.00	-0.01	0.02
	P5	0.00	0.38	0.16	0.01	0.34	0.13	-0.01	0.04	0.02
	P6	0.04	0.25	0.15	0.03	0.30	0.12	0.01	-0.05	0.04
	P7	0.02	0.30	0.17	0.03	0.29	0.17	0.00	0.01	0.00
	P8	0.00	0.32	0.18	0.00	0.32	0.18	0.00	0.00	0.00
Flow direction (°)	P1	103	290	118	94	298	117	9	-7	1
	P2	56	314	136	91	303	135	-35	11	1
	P3	95	340	164	105	337	167	-10	3	-3
	P4	39	319	168	18	337	178	21	-18	-9
	P5	2	359	167	10	342	168	-8	17	-1
	P6	1	359	104	7	356	147	-6	3	-42
	P7	0	360	114	0	360	119	0	0	-6
	P8	1	359	121	1	358	123	0	1	-2

3.3. Tidal discharge

Tidal discharge through the estuary increases slightly after dredging, reflecting improved channel conveyance. Peak ebb discharge ranges from approximately 400 to 600 m³/s under existing conditions and shows a consistent increase after channel deepening.

As shown in Figure 5a (northeast monsoon) and Figure 5b (southwest monsoon), the discharge curve under dredged conditions is consistently higher than that of the baseline scenario, particularly during ebb phases. This indicates enhanced drainage capacity and reduces hydraulic resistance.

However, the magnitude of change remains moderate, suggesting that dredging primarily affects flow efficiency and redistribution, rather than inducing major changes in the tidal regime.

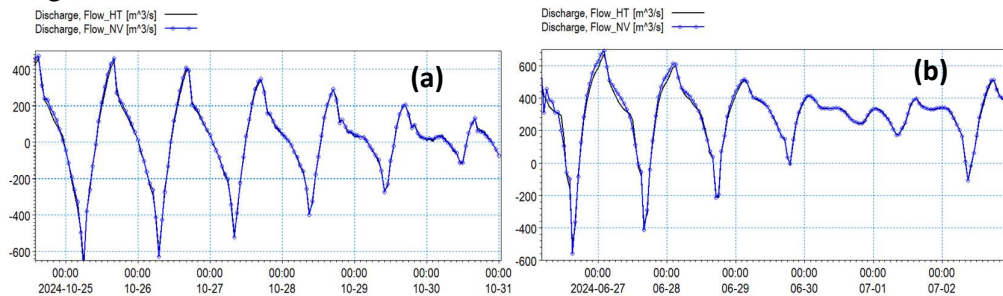


Figure 5. Comparison of tidal discharge at the estuary before and after dredging and sand mining under (a) northeast monsoon and (b) southwest monsoon conditions.

3.4. Discussion

The results indicate that dredging combined with sand mining primarily modifies channel geometry, leading to moderate changes in hydrodynamic conditions. The observed reduction in flow velocity is consistent with hydraulic responses to channel deepening, where an increase in cross-sectional area reduces flow resistance and redistributes discharge. Similar behavior has been widely reported in estuarine systems, where dredging can weaken residual circulation and reorganize velocity fields (van Maren, 2015; Winterwerp, 2013). The

concentration of flow along the main channel observed in this study reflects hydrodynamic adjustment to bathymetric modification, which is consistent with morphodynamic responses reported in engineered estuaries (Guo, 2014; Zhang et al., 2026).

The slight decrease in water level, particularly in upstream sections, can be attributed to bed lowering and associated changes in hydraulic gradients. Channel deepening is known to reduce bottom friction and alter tidal wave propagation, thereby affecting water level distribution along estuaries (Friedrichs, 2010; Winterwerp, 2013). More recent studies confirm that dredging can modify tidal amplitude and phase, although the magnitude of change is often limited in tide-dominated systems (Cox et al., 2022; van Maren, 2015). The relatively small variation observed in this study indicates that tidal forcing remains the dominant control, and the impacts of dredging and sand mining are mainly localized under normal conditions.

The increase in tidal discharge reflects enhanced channel conveyance capacity following dredging and sediment removal. This mechanism is consistent with studies showing that bathymetric deepening can increase tidal exchange and influence ebb–flood dynamics without fundamentally altering the overall hydrodynamic regime (Purkiani et al., 2021; Venancio et al., 2020). These findings suggest that combined dredging–mining activities primarily affect flow redistribution rather than inducing large-scale system shifts.

From a management perspective, reduced flow velocity and increased discharge capacity improve navigation conditions and hydraulic efficiency, which are key objectives of dredging and sand mining projects. However, the redistribution of flow may also alter sediment transport pathways. Recent studies highlight that sand mining can significantly modify sediment budgets, leading to localized erosion or deposition and affecting channel stability (Kennish, 2023). In addition, increased water depth may facilitate wave propagation toward nearshore areas, particularly under extreme conditions, thereby increasing the risk of coastal erosion and shoreline instability (Gou et al., 2023).

Overall, dredging combined with sand mining provides clear benefits for navigation and resource utilization but introduces potential environmental implications related to sediment dynamics and coastal processes. These results emphasize the need for integrated assessment approaches that consider both hydrodynamic and sediment responses, supporting sustainable resource management in estuarine systems.

4. Conclusion

This study assessed hydrodynamic changes induced by dredging combined with sand mining in the Tra Ly estuary using a coupled MIKE21 model. The results indicate a slight reduction in flow velocity, a minor decrease in upstream water levels (approximately 0.08 m), and a moderate increase in tidal discharge. These changes are mainly associated with channel deepening and expansion of the wetted cross-section, which enhance flow conveyance without significantly altering the overall tidal regime. Although the impacts remain limited under normal conditions, modifications in flow structure and tidal propagation suggest potential sensitivity under extreme events. The findings provide a quantitative basis for evaluating combined dredging–mining impacts and support sustainable resource management in estuarine systems.

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