

Effects of fish rafts on hydro-morphological changes: A case study in the Tien River, Vietnamese Mekong Delta

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ABSTRACT

The Vietnamese Mekong Delta, a critical global delta system, is experiencing severe morphological degradation marked by increasing riverbed incision. This instability is largely driven by large-scale anthropogenic factors, specifically upstream dam construction and sand mining. While these basin-wide impacts are well-documented, the localized hydro-morphological modification due to fish cages/rafts remains quantitatively underexplored. This study utilized a high-resolution two-dimensional (2D) hydro-morphodynamic model (e.g., MIKE 21 Flow Model FM) to quantify the effects of dense fish cage clusters on hydro-morphological changes along a critical segment of the Tien River in Dong Thap Province. The model, which demonstrated good performance (the Nash-Sutcliffe efficiency is equal to 0.78, 0.68, and 0.76 for discharge, suspended sediment concentration, and total sediment load, respectively, in model validation), compared the actual condition (Scenario A: with cages) against a baseline where fish cages were excluded (Scenario B: without cages). Simulation results showed that fish cages, clustered along the right bank, created a localized "bottleneck effect" forcing flow velocity to increase significantly in the open channel (mid-channel and left bank). This hydraulic alteration generated a strongly asymmetric sedimentation pattern. The accelerated flow intensified scour and erosion along the opposite (left) bank, with a mean incision depth reaching -0.8 m. Conversely, the right bank, located in low-velocity wake regions behind the structures, experienced substantial sediment accumulation, reaching more than +2.8 m in areas of the densest clustering. These findings confirm that concentrated fish

cage systems act as direct catalysts for localized morphological instability. This emphasizes the critical need to integrate hydro-morphological modelling into floating aquaculture spatial planning to optimize cage placement and mitigate the resulting cross-sectional imbalance.

INTRODUCTION

River deltas are vital, ecologically diverse, and densely populated regions globally, playing crucial roles across social, economic, environmental, and ecological dimensions (Chen et al., 2022). However, the stability and sustainability of these systems are increasingly threatened by intensifying human interventions (Evans, 2012; Brunier et al., 2014). Anthropogenic activities profoundly influence delta morphology by regulating water discharge and reducing critical sediment supplies (Menna et al., 2024). The adverse repercussions of these alterations manifest across various spatiotemporal scales, leading to changes in landforms, disruption of aquatic ecosystems, and increased salinity intrusion (Binh et al., 2022).

The Vietnamese Mekong Delta (VMD) is a crucial agro-aquaculture production hub, supporting approximately 19 million people (Ziv et al., 2012; Quan et al., 2018). However, the VMD has experienced severe and extensive morphological degradation, evidenced by a critical and increasing rate of riverbed incision (deepening) (Binh et al., 2022; Vu et al., 2024). Between 1990 and 2005, the VMD transitioned from a sedimentation-erosion equilibrium to a state where erosion clearly dominated (Thin, 2024). This instability is evidenced by increasing erosion hotspots;

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while approximately 99 erosion points were recorded across the delta in 2010, this number surged to 681 points by 2019 - a nearly sevenfold increase. Riverbank erosion, which is intrinsically linked to riverbed instability (Thin, 2024), has remained extensive, affecting 43% of the delta's riverbank length, posing a significant threat to settlements and agricultural land (Vu et al., 2024; Hackney et al., 2020; Binh et al., 2022; Park et al., 2022a).

This pervasive morphological degradation is primarily driven by two large-scale anthropogenic factors that have fundamentally altered the basin's sediment budget: upstream dam construction and intensive sand mining activities (Brunier et al. 2014, Kummur et al., 2010; Kondolf et al., 2014b, Li et al., 2017). Firstly, large-scale river damming in the upper Mekong basin, specifically the construction of six mainstream dams in the Lancang cascade, has led to a substantial reduction in the suspended sediment load (SSL) delivered to the VMD, ranging from 50% to 94% along the lower Mekong River (Kondolf et al., 2014; Manh et al., 2015). Overall, the completion of sixty-four dams across the Mekong basin has caused a severe reduction in the SSL by 74% within the VMD (Binh et al., 2020). This reduction turns the flow downstream into "sediment-hungry water", intensifying the erosion of riverbeds rather than facilitating sediment settling (Kondolf, G.M., 1997; Thao et al., 2014; Jordan et al., 2019; Binh et al., 2022). The forecasted consequences are drastic: the total net riverbed incision volume in the VMD was predicted to reach approximately 2,472 to 3,316 Mm³ between 2017 and 2026, depending on the magnitude of the suspended sediment reduction (18% and 85%, respectively) (Binh et al., 2022).

Secondly, accelerating sand mining activities within the VMD have exacerbated the morphological deterioration locally (Menna et al., 2024). Driven by demand for construction materials, licensed sand extraction volume escalated from 7.75 Mm³/year in 2012 (Bravard et al., 2013) to 29.3 Mm³/year in 2018 (Jordan et al., 2019). When unauthorized extraction is considered, the average volume reached 42 Mm³/year during 2015-2020 (Gruel et al. 2022). Sand mining permanently modifies the river's morphology and hydrodynamic characteristics by creating irregular depressions or pockmarks on the riverbed (Kondolf, 1997; Padmalal et al., 2008). This effect has been rigorously quantified: the contribution of licensed sand mining to annual net riverbed incisions rose from 27.7% in the 2005-2017 period to 35.3% in the 2017-2020 period (Menna et al., 2024). While river damming is the major trigger for large-scale incision, sand mining is the predominant factor contributing to the localized riverbed incision (Menna et al., 2024). Consequently, areas near sand mining hotspots, particularly in the upper reaches of the Tien River (Tan Chau to My Thuan), have transitioned to medium or high susceptibility levels for incision, with annual incision rates reaching up to -13 m/year (Menna et al., 2024).

While the broad, basin-scale impacts of damming and sand mining are well-documented, a third, highly localized anthropogenic factor is suspected of severely exacerbating instability in specific river reaches: the exponential growth of in-stream aquaculture systems, specifically fish cages and rafts. Indeed, the VMD is a vital aquaculture zone. In key provinces along the Tien River, such as Dong Thap, there are over 4,950 cages/rafts concentrated in areas like Cao Lanh and Sa Dec. These structures are often densely clustered along the riverbanks, effectively occupying and constricting the flow path. This physical presence creates a localized "bottleneck effect" forcing the flow through a reduced cross-sectional area. To maintain mass conservation (flow continuity), this constriction results in a significant localized increase in flow velocity and resultant bed shear stress in the

remaining unconstrained areas, typically the mid-channel and the opposite riverbank.

This hydrodynamic alteration is particularly problematic in the Tien River, where the upper reaches are already structurally weak due to underlying soft alluvium geology (Thin, 2024) and generalized deepening caused by regional sediment deficit (Lau et al., 2023; Menna et al., 2024). The flow constriction introduced by aquaculture cages can amplify the erosional capacity, concentrating destructive energy toward the opposite bank, thus accelerating localized erosion and instability. This is consistent with field observations showing severe erosion and the formation of deep scour holes near locations with dense aquaculture activity. Despite the clear visual evidence and hydraulic principles suggesting a strong localized impact, there is a conspicuous gap in specialized scientific literature that quantitatively models and isolates the hydro-morphological contribution of these fish cage systems. Previous morphodynamic research largely focuses on sediment budgets, overall basin changes, and the impact of large-scale extraction sites. To formulate sustainable management strategies, especially for integrated spatial planning of aquaculture and flood protection along the Tien River, a quantitative assessment of this specific localized human intervention is imperative.

Therefore, this study aims to apply a high-resolution 2D hydro-morphodynamic model to rigorously quantify the impact of fish cage/raft systems on the Tien River. The specific objectives are (1) to simulate and compare the flow velocity distribution and local hydrodynamic disturbance caused by the presence of dense fish cage clusters in a critical segment of the Tien River; (2) to quantitatively analyze the resulting asymmetrical riverbed changes, specifically detailing the localized enhancement of accretion and incision patterns; (3) to provide essential scientific data to support policy reforms related to aquaculture spatial planning and the long-term stability management of the Tien River.

Compared to existing studies that primarily focus on basin-scale drivers such as upstream dam construction and sand mining, this study provides a quantitative, reach-scale assessment of the localized hydro-morphological impacts induced by dense fish cage systems. By explicitly isolating the effects of fish cages through Scenario-based numerical simulations, this work demonstrates that in-stream aquaculture structures can act as direct hydraulic modifiers, generating asymmetric flow redistribution and localized erosion-accretion patterns. This contribution bridges an important knowledge gap between large-scale sediment budget analyses and localized riverbank instability processes. The findings therefore complement existing Mekong Delta studies by highlighting an additional, highly localized anthropogenic driver of morphological change.

Study area

The VMD (Fig. 1) is located in the estuary of the 4,900 km long Mekong River, which ranks as the 12th longest river globally (Jordan et al., 2019). The delta receives an annual water discharge ranging from 300 to 550 km³ (Binh et al., 2022). It is characterized by an alluvial bed with a very mild slope. The Mekong River splits into the Tien River and the Hau River upon entering Vietnam at the Tan Chau and Chau Doc stations, respectively. Historically, the Tien River conveyed 80-95% of the total discharge, but the Vam Nao Channel has realigned this balance to approximately 51% for the Tien River and 49% for the Hau River downstream (Binh et al., 2022).

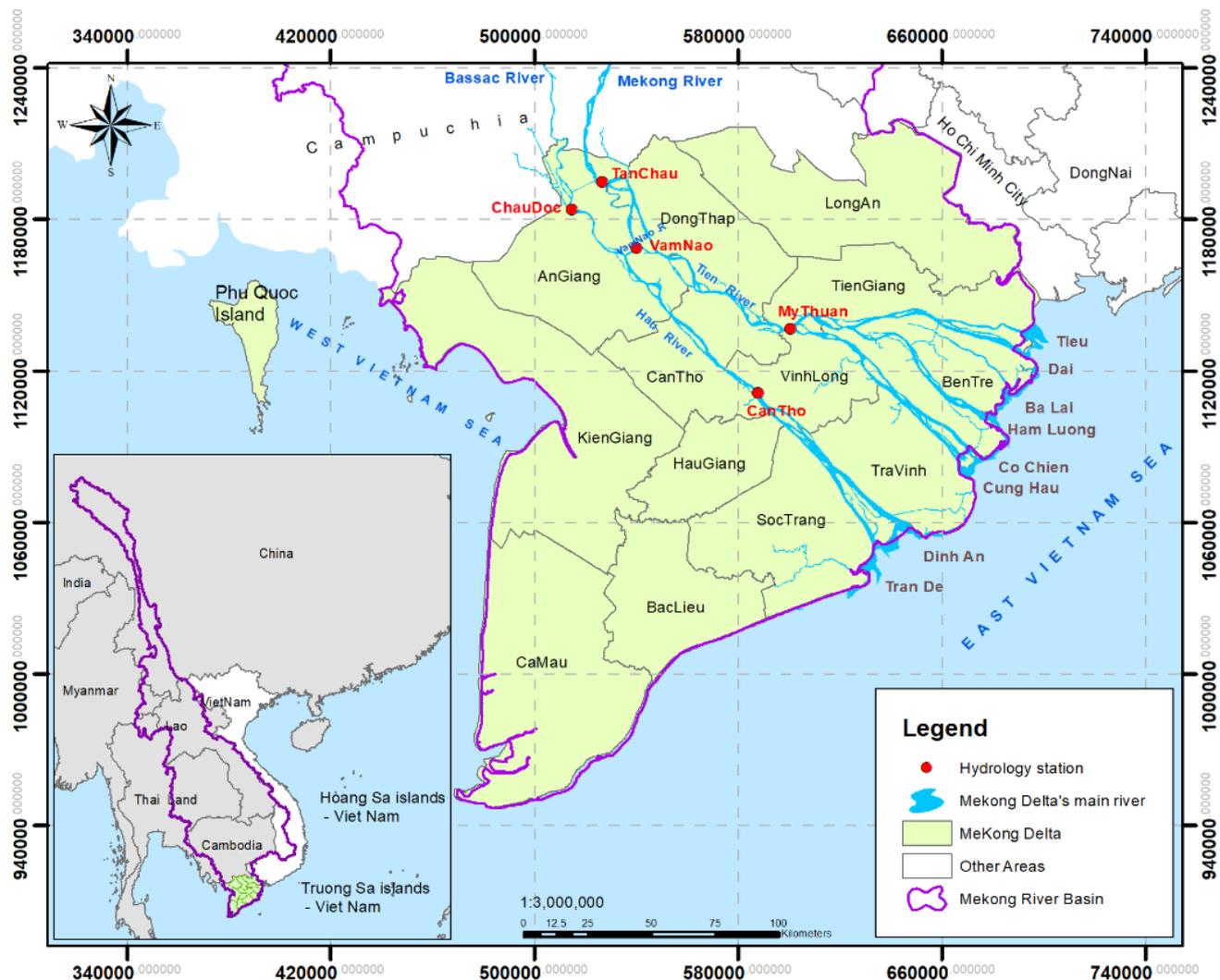


Figure 1: Vietnam Mekong Delta

The VMD experiences a distinct seasonal flow regime shaped by a monsoonal climate, with high flow (flood season) running from July to December and low flow (dry season) from January to June (Binh et al., 2022; Menna et al., 2024). The delta occupies a unique transitional zone, shifting from a fluvial-dominated zone upstream to a tide-dominated zone downstream (Gugliotta et al., 2017). The demarcation line for this transition occurs near the My Thuan and Can Tho gauging stations (Nowacki et al., 2015). The riverbed

elevations of the Tien and Hau Rivers vary significantly, ranging from a few meters near the river mouths to exceeding 30 m in the upper reaches (Nowacki et al., 2015). Our study focuses on a critical segment of the Tien River located in the upper reaches, specifically within Dong Thap Province, near the confluence zone of Cao Lanh - Sa Dec. This area is situated in the fluvial-dominated, tide-affected zone of the VMD (Fig. 2).

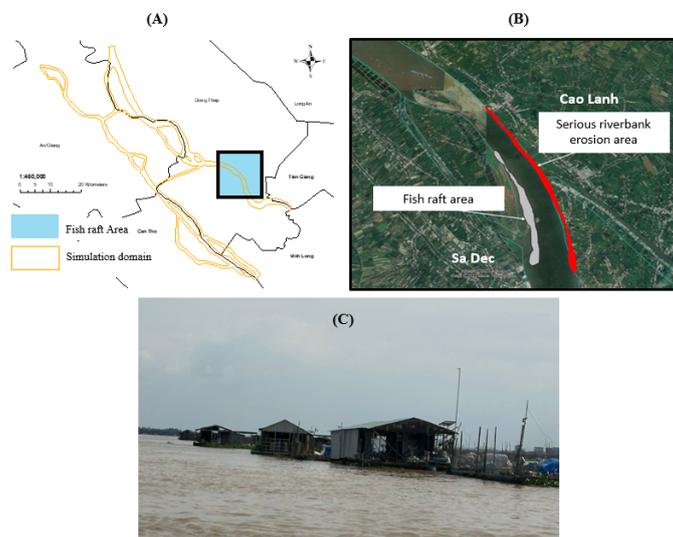


Figure 2: Simulation domain in the Tien and Hau Rivers (A) with the studied fish raft region in the Tien River (B). C) Typical photo of fish cages in the study area.

The upper reaches of the Tien River (Tan Chau to My Thuan) have consistently exhibited significant increases in riverbed incision volume over recent periods (Menna et al., 2024). Mean riverbed elevations in the upper Tien River declined from -8.26 m (1998) to -12.05 m (2020) (Menna et al., 2024). The deepest stretches are predominantly localized upstream, notably within the meandering stretch near Sa Dec city (Menna et al., 2024). This region exhibits high susceptibility to incision, with annual incision rates reaching 13 m/year in areas downstream of Sa Dec city between 2017 and 2020 (Menna et al., 2024). This morphological volatility is exacerbated by active sand mining operations in the Sa Dec and Vinh Long regions, contributing to sediment depletion and accelerating incision (Jordan et al., 2019; Gruel et al., 2022; Lau et al., 2023). Particularly, in Dong Thap Province, the annual legal sand mining volume increased from 9.5 Mm³ in 2015 to 9.88 Mm³ in 2017-2020 (Menna et al., 2024).

The Cao Lanh-Sa Dec section of the Tien River experiences intensive aquaculture development and significant human intervention (Fig. 2). Dong Thap Province has more than 4,950 fish cages and rafts, mainly concentrating along the riverbanks in the vicinities of Cao Lanh and Sa Dec. Recent field surveys (2024) and previous research have documented severe morphological imbalances within this river segment. The left bank (Cao Lanh side) exhibits pronounced erosion and lateral encroachment, with some areas reaching up to approximately 5 m inland. This zone is typified by dangerous vertical scour holes and steeply undercut banks that undermine local stability. Recorded depths of these scour holes range from -24 m to -30 m, posing serious risks to adjacent agricultural lands and riverbank infrastructure. In contrast, the right bank (Sa Dec side), where aquaculture cages and rafts are primarily clustered, demonstrates a pattern of sediment accretion, with the formation of a large sandbar or accretion zone extending roughly 100 m into the river channel. The delineation of this specific section enables a detailed and spatially explicit analysis through high-resolution numerical modelling, facilitating the direct assessment of the relationship between the distribution of intensive aquaculture structures and the observed asymmetrical morphological evolution of the riverbanks.

MATERIALS AND METHODS

General methodology

The study utilizes a quantitative approach based on a two-dimensional (2D) hydro-morphodynamic numerical model (MIKE 21) to simulate the intricate relationship between flow dynamics, sediment transport, and riverbed evolution. This modelling approach is crucial for predicting scour hole formation and associated riverbank instability. Figure 3 shows the methodological framework used to analyze the hydrodynamic and morphological impacts of fish-raft aquaculture using the MIKE 21 model. We first collected necessary data, including bathymetry, discharge, water level, and locations and extents of fish cages and rafts. These datasets were processed to input as boundary conditions for the MIKE 21 model.

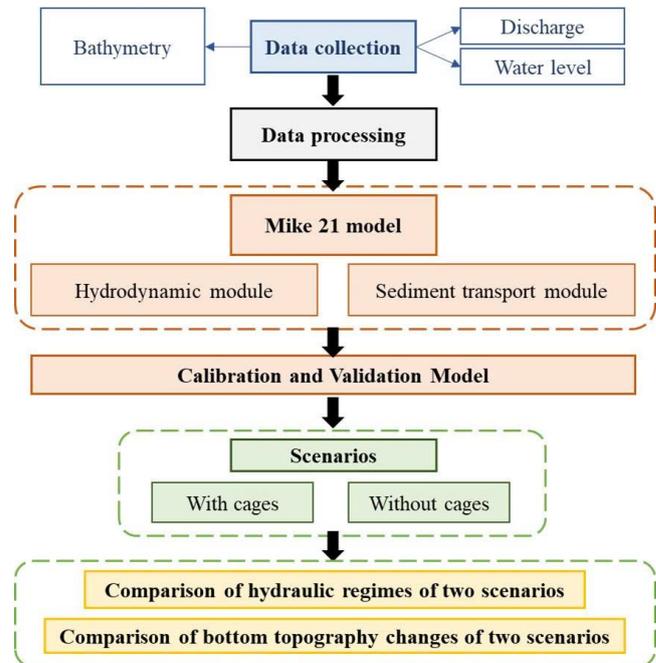


Figure 3: The methodological framework

The MIKE 21 model considers two key components: the hydrodynamic and sediment transport modules. The hydrodynamic module simulates water level and flow velocity, while the sediment transport module simulates suspended sediment and bedload transport and their interaction with riverbed evolution. We calibrated and validated the model using observed data. After that, we simulated two scenarios, namely (1) with cages (representing actual conditions in the study area) and (2) without cages (representing the natural state without human intervention). We compared the differences in hydraulic regimes and riverbed evolution between these two scenarios to evaluate the effects of fish rafts on hydro-morphodynamics.

Numerical modelling framework

We used the MIKE 21 Flow Model FM (MIKE 21FM), developed by the Danish Hydraulic Institute (DHI), which employs a flexible unstructured mesh based on the finite element method to accurately represent complex river geometries, including river bends and near-bank structures. The model couples the hydrodynamic (HD) and sediment transport (ST) modules, in which the HD module solves the two-dimensional depth-averaged Navier-Stokes equations to simulate water levels and flow velocities, while the ST module computes sediment transport rates and associated riverbed evolution. A two-dimensional (depth-averaged) modelling approach was adopted because the dominant processes examined in this study-lateral flow redistribution, near-bank velocity enhancement, and reach-scale sediment redistribution induced by fish cages-are effectively captured by 2D models. Moreover, this approach provides a suitable balance between physical realism and computational efficiency for multi-year simulations over large river domains.

Computational domain and mesh

The simulation domain covers the upper part of the Tien and Hau Rivers, from Tan Chau to My Thuan in the Tien River and from Chau Doc to Can Tho in the Hau River (Fig. 4). We established an unstructured mesh, consisting of 8,126 nodes and 13,464 elements, representing both the river channel and adjacent riverbank areas. Finer mesh size was considered for narrower river segments and around irregular shapes, while coarser mesh size was used for regular, wide river segments. The maximum element size is approximately 485 m, while the minimum element size is 15 m, providing a detailed representation of the riverbed and near-bank zones. For the fish raft area, the grid resolution was further refined, with a minimum element size of 1 m, to accurately capture local

hydraulic variations and flow disturbances caused by the dense fish-cage structures.

The topographic database used to construct the computational mesh and define the hydraulic boundary of the study area was derived from detailed field surveys. The 2019 topographic data were processed at a spatial resolution of 5×5 m in the core study area and 50×50 m in other regions. Riverbed elevation data were measured in 2019 using an Acoustic Doppler Current Profiler (ADCP) integrated with GPS positioning. The raw data, in “.txt” format, were processed and cleaned using GIS software tools, including ArcGIS and Global Mapper. These processed data were

then interpolated to create the digital elevation model (DEM) used in the model setup and hydraulic simulations.

The 2019 bathymetric data were used as a static initial bed condition for the morphodynamic simulations, while hydrodynamic and sediment transport calibration was conducted using time-series data from 2018. This approach is commonly adopted in large-scale morphodynamic studies when repeated bathymetric surveys are unavailable (Thanh et al., 2025; Binh et al., 2022).

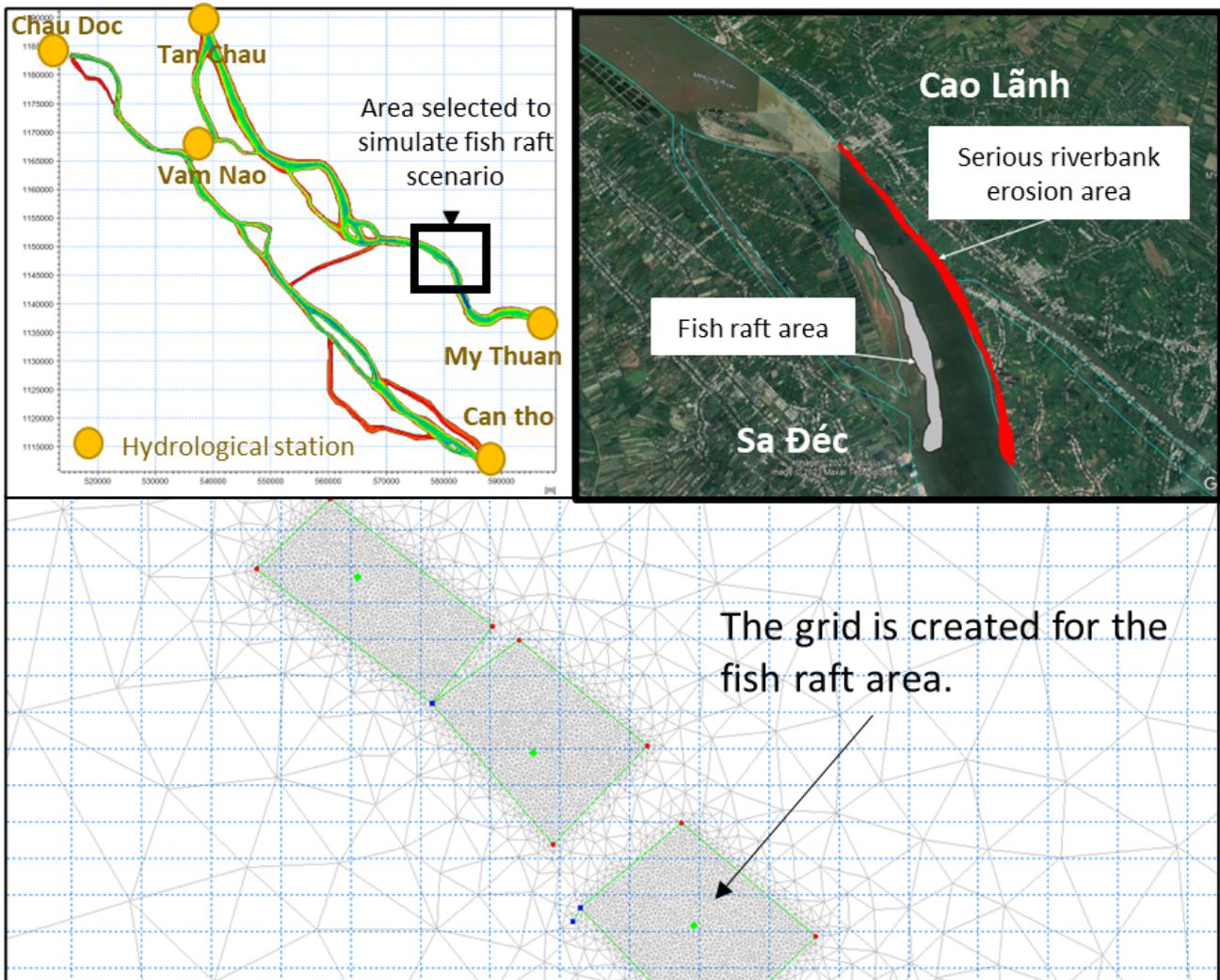


Figure 4: Mesh of the simulation domain and grid created for the fish raft area in the Tien River

Boundary Conditions

The simulation domain had four boundaries, including two upstream and two downstream boundaries. The upstream boundaries were specified using hourly flow discharge and daily suspended sediment concentration (SSC) data from the Chau Doc and Tan Chau hydrological stations, while the downstream boundaries were defined using hourly water level data from the My Thuan and Can Tho hydrological stations. We used the water level and SSC at the Vam Nao station to calibrate and validate the model. The simulation period was from 00:00 on January 1, 2017, to 23:00 on December 31, 2019 (three years).

Simulation scenarios

We simulated two scenarios, namely “with cages” and “without cages”, to assess the effects of fish rafts on hydrodynamics, sediment transport, and morphological changes. Scenario A (with cages) represents the actual river conditions, considering the physical obstruction of the dense fish-cage system located in the

Cao Lanh-Sa Dec reach. The fish cages were implemented as flow-blocking structures within the flexible mesh framework of MIKE 21, locally reducing the effective flow area and increasing hydraulic resistance. A refined mesh was applied around the cage clusters to capture localized velocity gradients, flow separation, and wake effects. This representation allows the physical presence of fish cages to influence local flow velocity, bed shear stress, and sediment transport capacity, thereby affecting erosion and deposition processes. Scenario B (without cages) serves as the baseline condition, representing the natural state of the river without fish cages. This configuration provides a reference for assessing the hydrodynamic effects caused by fish cages. By comparing the outcomes of these two scenarios, the study quantifies the influence of fish rafts on flow velocity, sediment transport, and morphological changes along the Tien River. The shape, size, and spatial distribution of fish cages were derived from field surveys conducted in 2024, complemented by local

management records and satellite imagery. No idealized or hypothetical cage configurations were assumed in the simulations.

RESULTS AND DISCUSSION

Model calibration and validation

We used the 2018 discharge, SSC, and total sediment load (TSL) at Vam Nao for model calibration and validation. The model was calibrated for the dry season (January-June) and validated for the flood season (July-December). To assess the reliability of the model results, the Nash-Sutcliffe efficiency (*NSE*) and the coefficient of determination (*R*²) were used as performance metrics. The calibration and validation process involved adjusting

key numerical and physical parameters, including bed resistance, grain size, Manning roughness coefficient, settling velocity, erosion and deposition coefficients, and bed layer properties to improve the agreement between simulated and observed data. The model was run 100 times during calibration to achieve reasonable results, and the final parameter values are presented in Table 1. In the hydrodynamic module, the Manning roughness coefficient had the greatest impact on (tidal) water level fluctuations and flow dynamics. To account for vertical variability, a depth-dependent Manning roughness was applied, with higher values in deeper areas. In the sediment transport module, settling velocity, together with erosion and deposition coefficients, were the most sensitive parameters affecting sediment dynamics and riverbed evolution.

Table 1: Final numerical and physical values of the validated model

Parameter	Value	Unit
Hydrodynamic module		
Friction law	4 (Manning)	
Friction coefficient	0.015 – 0.032	m ^{1/3} /s
Turbulence model	2 (Elder)	
Kinematic viscosity	10 ⁻⁶	m ² /s
Secondary currents	✓	
Wave effect on flow	✓	
Tidal flats	✓	
Sediment transport module		
Sediment type	Mixed sediment	
Grain diameter	0.32 (sand); 0.025 (mud)	mm
Porosity	0.375	
Number of bed layers	2	
Active layer thickness	0.05	m
Mud content per layer	75; 85 (from top to bottom)	kg/m ³
Critical shear stress for mud erosion	0.025; 0.085	N/m ²
Critical shear velocity for mud deposition	1000	m/s
Partheniades constant	0.001	kg/m ² /s
Slope effect (Soulsby, 1997)	✓	
Equilibrium mud-sand content near bed	Zyserman and Fredsoe (1994)	
Settling velocity	0.15 (sand); 0.032 (mud)	mm/s
Bed roughness	ks' = 3d ₅₀	mm

Table 2 shows the results of the model calibration and validation at the Vam Nao hydrological station for both the hydrodynamic (discharge) and sediment transport (SSC and TSL) modules. The model demonstrated good performance in both calibration and validation phases. For the hydrodynamic module, *NSE* for discharge ranged from 0.75 to 0.78, while *R*² varied between 0.76 and 0.82 for the model calibration and validation, respectively. These values indicate that the simulated discharge aligned well with the observed data, implying that the selected model parameters were robust and reliable. In other words, the validated hydrodynamic module can be reliably used for the sediment transport module. For the sediment transport module, *NSE* ranged from 0.68 to 0.76, and *R*² ranged from 0.66 to 0.8 for SSC and TSL, respectively, in model validation (Table 2). Figure 5 confirmed that the simulated SSC and TSL agreed well with the observed data. Notably, the overall error in TSL was only 6.54%, which is considered a satisfactory value for sediment transport model

validation. Overall, these results demonstrate that the validated model is capable of reproducing spatiotemporal hydrodynamics and sediment transport in the study area, providing confidence in its application for further analyses in the assessment of fish rafts on hydro-morphological alterations.

Table 2: Performance metrics for the hydrodynamic and sediment transport modules at the Vam Nao hydrological station for model calibration and validation

Parameter	Types	<i>R</i> ²	<i>NSE</i>
Discharge	Calibration	0.76	0.75
	Validation	0.82	0.78
SSC	Calibration	0.67	0.67
	Validation	0.66	0.68
TSL	Calibration	0.81	0.77
	Validation	0.80	0.76

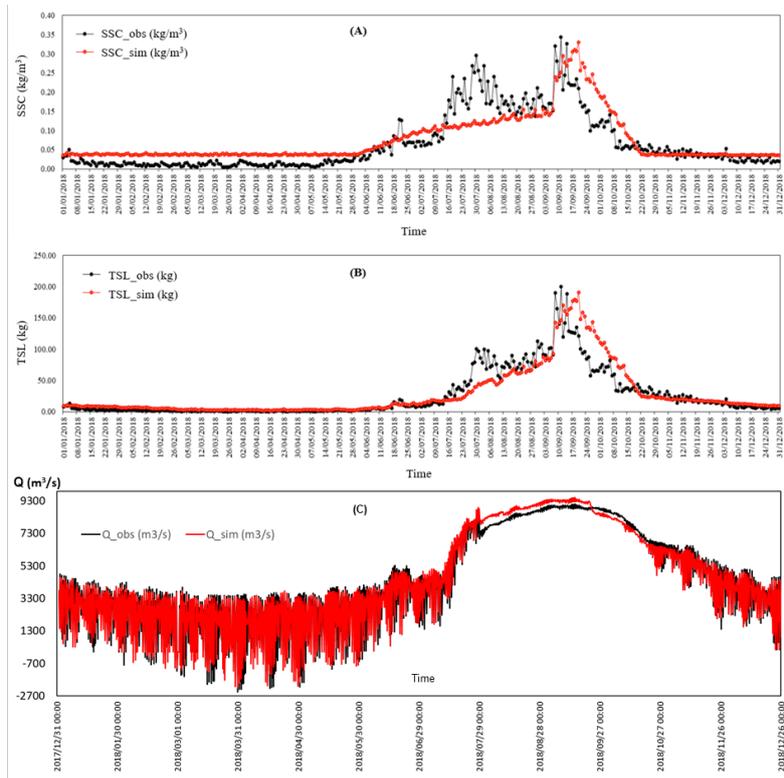


Figure 5: Simulated vs observed SSC (A), TSL (B) and Q (C) at the Vam Nao hydrological station for model calibration and validation.

Effects of fish rafts on velocity distribution in the river

Simulation results show that the presence of nearshore fish cage systems substantially modifies the flow velocity distribution (Fig. 6). Under the scenario without fish cages, flow velocity is relatively uniform across the channel, with the highest velocities concentrated near the river center and decreasing toward the banks.

In curved reaches, flow tends to follow the channel curvature. However, fish cages create a “bottleneck” effect for flow velocity distribution, by shifting the main flow to the river center and the opposite side of the fish cages.

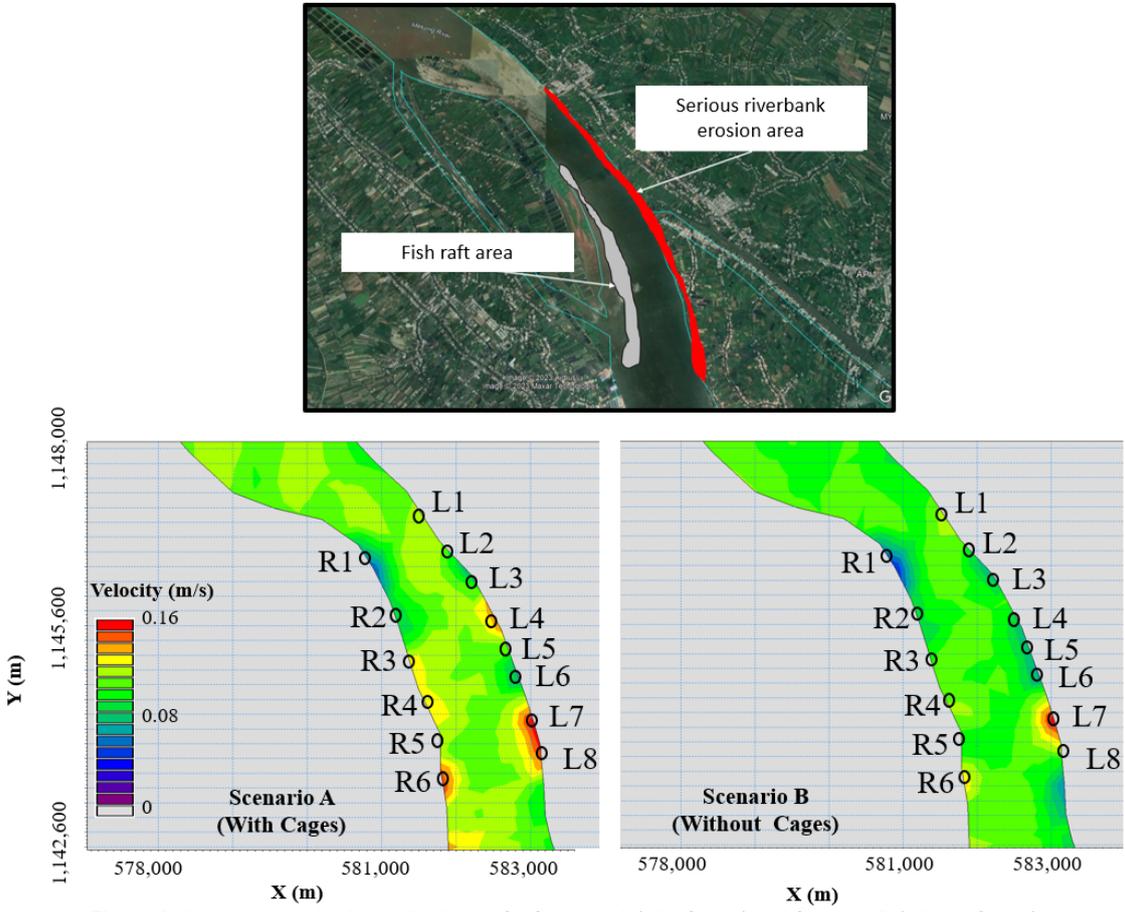


Figure 6: Average annual velocity distribution for Scenario A (with Cages) and Scenario B (without Cages).

Table 3: Average annual velocities at along the riverbanks. Locations are shown in Figure 6. L: left bank; R: right bank.

Location	Flow velocity (m/s)	
	Scenario A (with cages)	Scenario B (without cages)
L1	0.12	0.11
L2	0.11	0.08
L3	0.11	0.08
L4	0.14	0.09
L5	0.1	0.08
L6	0.08	0.07
L7	0.16	0.14
L8	0.16	0.13
R1	0.06	0.06
R2	0.08	0.07
R3	0.13	0.1
R4	0.13	0.11
R5	0.12	0.1
R6	0.16	0.13

The effect of fish cages on flow dynamics was evident at most measured locations (e.g., L2–L5, L7–L8, R3–R6) (Fig. 6 and Table 3), where velocities under Scenario A consistently exceeded those under Scenario B. This pattern can be attributed to the localized flow obstruction created by the cages, which increased velocity gradients in adjacent areas and concentrated flow through the gaps between structures. For instance, velocities at L2 and L3 increased from 0.08 m/s to 0.11 m/s, while R3 experienced an increase from 0.10 m/s to 0.13 m/s in Scenario A compared to Scenario B, highlighting the capacity of cage arrangements to modify local hydrodynamics.

In contrast, other locations (e.g., L1, L6, R1, R2) showed minimal velocity changes (0.01–0.02 m/s), suggesting that the influence of fish cages was limited in these areas. This minimal impact may be due to naturally low baseline velocities or the relatively small portion of the flow cross-section obstructed by the cages. These results indicate that the effect of fish cages on flow velocity is highly spatially variable, depending on both local hydrological conditions and cage arrangement.

A comparison between banks revealed that flow velocities along the left bank (concave side) were generally higher than those along the right bank (convex), particularly at L7–L8, where velocities reached 0.16 m/s in the presence of cages. This asymmetry may be associated with river morphology and the preferential concentration of flow induced by the cage structures. Overall, fish cages appear to enhance velocities in their immediate vicinity due to flow diversion, while potentially reducing velocities directly beneath the cages, whereas areas farther from the structures or near the channel center remain largely unaffected.

Furthermore, downstream of the fish cage clusters, e.g., in areas where the bank is obstructed, localized vortex zones (R3, R4, R5, R6) were observed, with markedly increased flow velocities resulting from backflow effects and flow disturbances around the obstacles. These zones not only alter local flow velocities but also influence sediment dynamics and bank erosion potential. Simulation results indicate that velocities in these regions can be substantially higher than in corresponding areas without fish cages, thereby elevating the risk of bank erosion, slope instability, and adverse impacts on the riverine ecological environment.

Overall, the model results demonstrate that the presence of fish cages significantly modifies the flow velocity distribution across the Tien River, affecting both the central channel and near-bank areas. The altered flow may modify the sediment transport and riverbank instability, resulting in ecological degradation. These findings highlight the importance of carefully managing fish cage locations and arrangement to mitigate adverse effects on the surrounding hydrodynamics and riverine ecosystems.

It should be noted that the reported velocity differences primarily represent relative modifications in flow patterns rather than absolute thresholds for sediment mobilization. In sediment-starved and morphologically unstable systems such as the Tien River (Vu et al., 2024; Thinh, 2024; Binh et al., 2022; Park et al., 2022a; Hackney et al., 2020), even modest increases in near-bank velocity can substantially enhance bed shear stress and sediment entrainment, thereby amplifying erosion processes over time.

Effects of fish rafts on riverbed changes

Figure 7 compares mean riverbed elevation changes between the with and without cages scenarios from 1/1/2017 to 31/12/2019. It can be seen that fish cages may generate localized depositional zones near the right bank and intensified erosion along the left bank due to modifying the flow velocity. Under Scenario A (with cages), fish cages reduce the effective flow area near the right bank, forcing the main current toward the mid-channel and left bank. This diversion increases local flow velocity and bed shear stress in the left-bank corridor, which in turn enhances sediment entrainment and scour. The simulated erosion zones along the left bank are continuous and deeper compared to the corresponding locations in Scenario B (without cages), where the absence of cages maintains a more uniform flow profile. In contrast, the right bank exhibits pronounced sediment accumulation immediately behind and downstream of the cages. These depositional mounds are formed in low-velocity wake regions created by the flow obstruction of the cages, where suspended and bedload sediments settle. The combination of accelerated flow near the left bank and decelerated flow behind the right-bank cages leads to a strongly asymmetric sedimentation pattern, reshaping the channel bed morphology over time.

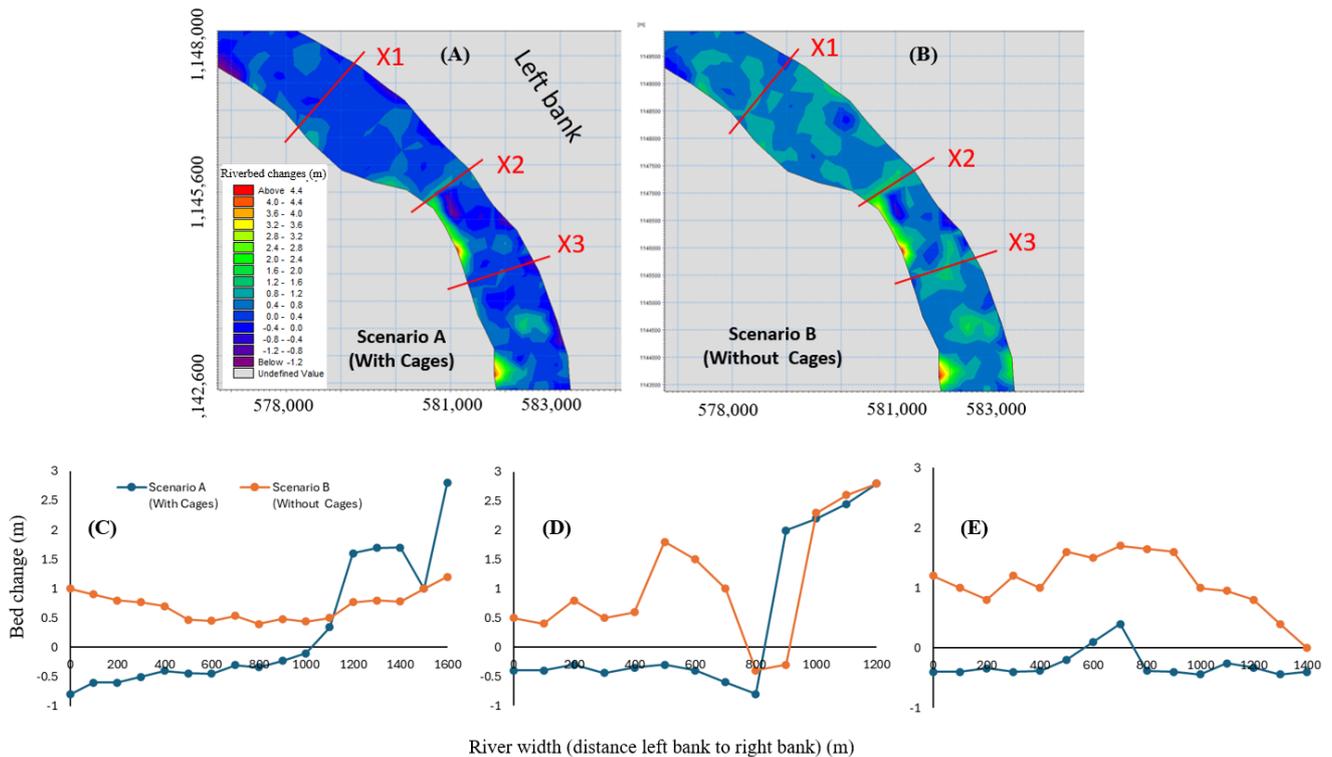


Figure 7: Average annual bed changes during 2017-2019 in **A)** Scenario A (with cages) and **B)** Scenario B (without cages). Sub-figures **C**, **D**, and **E** show typical cross sections X1, X2, and X3, respectively.

To provide a more detailed assessment, three representative cross sections (X1, X2, and X3) were examined across the channel width under both simulation scenarios (Fig. 7C-E). At cross section X1, located in the upstream part of the study reach, differences between the two cases are evident. In Scenario B (without cages), bed elevation changes remain mostly positive across the width, indicating mild aggradation under natural conditions. However, in Scenario A (with cages), the channel bed near the left bank (0-900 m) exhibits distinct negative elevation changes, with erosion depths reaching -0.8 m, while the right-bank section (1000-1600 m) shows positive elevation gains of up to +2.8 m. This spatial contrast indicates that the fish cages shifted sedimentation patterns laterally—scour dominates on the left bank, while deposition occurs immediately downstream of the cage clusters on the right bank. The sheltering effect of the cages reduces local velocities near the right bank, promoting sediment settling and aggradation.

At cross section X2, located mid-reach and near the densest cluster of cages, the magnitude of riverbed change is even more pronounced. In scenario B, the bed elevation varies moderately between -0.4 and +2.8 m across the channel, showing balanced sediment transport. In Scenario A, however, the left bank (0-800 m) experiences severe scouring, while strong deposition occurs in the right-bank region (900-1200 m), where bed elevation rises by more than +2.8 m. The concentration of fish cages near the right bank constricts the flow area, intensifying velocity gradients and turbulence across the mid-channel. Consequently, riverbed is eroded from the left side and advected laterally toward lower-energy zones behind the cage areas. This pattern demonstrates that the hydraulic interference of fish cages does not remain localized but instead alters the entire cross-sectional sediment distribution through enhanced lateral sediment transport.

At cross section X3, located downstream of the cage system, the morphological response remains evident but less intense. In Scenario B, mild aggradation is observed along the mid-channel and both banks. In contrast, scenario A exhibits persistent erosional signals across most of the section (0-1000 m), with only limited deposition near the right bank (around 1400-1600 m). This suggests that even though the influence of the cages attenuates

downstream due to energy dissipation, the overall sediment redistribution persists. The continued erosion on the left bank reflects the inertia of the high-velocity core that was diverted from the cage area upstream. Meanwhile, residual deposition near the right bank indicates that low-energy eddies and recirculation zones still promote sediment trapping, even several hundred meters downstream.

Synthesizing the results from the three cross sections reveals three key findings. *First*, fish cage placement near the right bank creates a distinct lateral asymmetry in morphological evolution: erosion intensifies on the opposite (left) bank, while deposition accumulates near and behind the cages. *Second*, the magnitude of these changes peaks in the middle section (X2), where flow constriction is greatest, suggesting that both cage density and cross-sectional blockage ratio critically influence bed response. *Third*, the alternation between zones of scour and deposition along the channel width implies that cage-induced turbulence and secondary flow structures drive complex patterns of sediment redistribution rather than uniform morphodynamic adjustments.

From a hydraulic perspective, these responses are consistent with established fluvial processes. The cages act as semi-permeable roughness elements that modify near-bank velocity fields, producing localized flow separation, vortex shedding, and wake recirculation (Nepf, 2012). These turbulent structures decrease the stream's transport capacity behind the cages, favoring sediment deposition, while the accelerated core flow on the opposite side increases erosive potential. Over time, such interactions between hydraulic forcing and sediment transport reinforce the morphological asymmetry: the right bank becomes a zone of net aggradation, while the left bank experiences progressive deepening and lateral retreat (Redolfi, 2021).

Seasonal analysis indicates that cage-induced erosion is most pronounced during the flood season, when higher discharges amplify velocity redistribution and bed shear stress. During the dry season, reduced flow energy favors deposition in wake zones behind cages. This seasonal contrast reinforces the cumulative asymmetric morphology observed in annual averages.

The geomorphic consequences of these alterations extend beyond local bed changes (Wohl et al., 2015). Continuous scour holes along the left bank may threaten bank stability, potentially leading to undercutting and riverbank collapse (Binh et al., 2022; Park, 2024). In contrast, excessive deposition along the right bank near the cages may reduce local flow conveyance and affect navigation (Abbasian et al., 2023). Ecologically, the heterogeneity of bed substrates and flow habitats created by the cage-induced morphology may favor certain benthic communities while degrading others, thereby altering local ecosystem balance (Kalantzi and Karakassis, 2006; Varol, 2019). Furthermore, repeated or large-scale deployment of cage systems could exacerbate these patterns, cumulatively modifying channel geometry and sediment connectivity at the reach scale (Rickard, 2020).

Overall, the comparative analysis of Scenarios A and B clearly demonstrates that fish cage systems, when concentrated along one bank, substantially modify both hydraulic and sedimentary dynamics across the entire channel width. The resulting asymmetry, characterized by aggradation on the one bank and erosion on the opposite bank, represents a direct physical consequence of altered flow distribution and turbulence patterns. These findings emphasize the need for spatially informed floating aquaculture management strategies. Cage placement should be optimized to minimize hydraulic constriction and cross-sectional imbalance, potentially through alternating bank deployment, spacing adjustments, or maintaining buffer zones between cage clusters and the bank.

From a management perspective, these findings highlight the importance of integrating hydro-morphological considerations into floating aquaculture spatial planning. Concentrated cage placement along a single riverbank should be avoided, as it can induce strong cross-sectional imbalance and localized erosion. Optimized cage spacing, alternating bank deployment, or the establishment of buffer zones between cage clusters and the riverbank could help mitigate hydraulic constriction and associated morphological impacts.

CONCLUSION

The VMD is a vital, ecologically diverse, and densely populated region that is simultaneously experiencing severe and extensive morphological degradation, primarily evidenced by a critical and increasing rate of riverbed incision. This widespread instability is historically driven by basin-scale anthropogenic factors, including upstream dam construction and sand mining. This study addressed a significant scientific gap by quantitatively modelling and isolating the effects of fish cages/rafts on localized hydrodynamic modification and morphological changes along the critical Tien River reach using MIKE 21 Flow Model FM. We assessed the effects of fish cages on hydro-morphological changes by comparing Scenario A (with cages) with Scenario B (without cages) after obtaining a reliable model's validation results (NSE = 0.78, $R^2 = 0.82$ for discharge; NSE = 0.68, $R^2 = 0.66$ for SSC; NSE = 0.76, $R^2 = 0.80$ for TSL).

Simulation results revealed that the nearshore fish cage systems substantially modified the flow velocity distribution. The dense placement of cages, particularly along the right bank in the study area, created a localized "bottleneck effect". This flow constriction forced velocities to increase significantly in the remaining open channel, primarily near the mid-channel and the opposite (left) bank, to maintain mass conservation. For instance, velocities at locations L2 and L3 increased from 0.08 m/s to 0.11 m/s due to the cage arrangements. Furthermore, the model identified localized vortex zones with heightened flow velocities downstream of the cage clusters, which are associated with backflow effects and flow

disturbances, thereby elevating the risk of bank erosion and slope instability.

The numerical simulations demonstrated that the hydraulic interference from the cages generated a strongly asymmetric sedimentation pattern across the channel width. On the one hand, the diverted, accelerated flow due to the fish cages intensified sediment entrainment and scour along the opposite (left) bank. The left bank experienced severe scouring, with persistent erosional signals continuing downstream of the cage system. On the other hand, the areas immediately behind and near the cages on the right bank (operating as low-velocity wake regions) experienced pronounced sediment accumulation. At cross section X2, which represents the densest cluster, this deposition resulted in the right bank gaining bed elevation by more than +2.8 m.

This study provides quantitative evidence that densely concentrated fish cage systems act as direct catalysts for localized morphological instability. The resulting lateral asymmetry (characterized by right-bank aggradation and accelerated left-bank erosion) is a direct physical consequence of the altered flow distribution and turbulence patterns caused by these structures. These findings underscore the critical need to integrate hydro-morphological modelling into floating aquaculture planning. Although the magnitude of the observed impacts is site-specific, the underlying mechanisms—flow constriction, lateral velocity redistribution, and wake-induced sediment deposition—are generic. Therefore, the findings are applicable to other river sections with dense near-bank aquaculture structures, particularly in sediment-deficient river systems. To mitigate the adverse impacts on the stability of the Tien River, future management strategies should be spatially informed, focusing on optimizing cage placement to minimize hydraulic constriction and cross-sectional imbalance, potentially through methods such as spacing adjustments or maintaining buffer zones.

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CONFLICT OF INTEREST

The authors declare no competing interests.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

NXT: Secured funding, developed the conceptual framework, designed methodology, performed data curation and formal analysis, and drove the original and final drafts. LDN: Developed the conceptual framework and designed methodology. NKD, BTBA, PTH: Edited the original draft and reviewed the final manuscript. PDH, NTN, NTL, DTT: Edited and reviewed the final manuscript.

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