Assessment of riverbed evolution in the Vam Nao River under the influence of sand mining using a numerical model

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ABSTRACT

Riverbed sand mining is a major anthropogenic driver of sediment imbalance and riverbank erosion in the Mekong Delta. This study investigates its morphological impacts using the hydrodynamic–morphological model HYDIST, coupled with a sand mining source function (S_{sm}), to directly simulate unsustainable sand mining. The model is applied to the Vam Nao River, a confluence connecting the Tien and Hau rivers. Unlike conventional approaches that assume static mining pits, sand mining is represented here as a dynamic process by incorporating the source function directly into the bed evolution equation, allowing a more realistic description of mining–morphology interactions.

Simulation results show that sand mining markedly intensifies riverbed erosion and disrupts the natural erosion–deposition balance. In the Vam Nao River reach (Zone 1), the proportion of deposition declines from 27.1% to 12.9%, while erosion increases to 87.1% of total morphological change, indicating a transition toward an erosion-dominated regime. In the Hau River reach (Zone 2), which is naturally depositional with deposition accounting for up to 83.77% under non-mining conditions, sand mining completely reverses the morphological pattern. The total erosion volume becomes 8.4 times greater than that in the non-mining scenario. At the Vam Nao–Hau River confluence (Zone 3), deposition volume decreases by 30.2%, and erosion represents 69.56% of total morphological change, highlighting a strong downstream propagation of mining impacts. The results demonstrate that sand mining substantially enhances morphological instability, particularly in river confluence zones, and that these zones play a critical role in amplifying the effects of upstream sand mining.

Keywords: Sand mining; Riverbed morphology; Hungry water; Sediment budget; Mekong Delta

(1) This is a non-peer reviewed preprint on EarthArXiv, and (2) the manuscript is also under review at Hydrology Research.

HIGHLIGHTS

- Sand mining shifts the river from balanced conditions to strong erosion, rapidly deepening the riverbed.
- Areas that once trapped sediment begin eroding, increasing risks of bank collapse and channel instability.
- Impacts spread downstream, showing that mining effects extend far beyond the extraction sites.

1. INTRODUCTION

Sand mining is a dual nature activity, as it can both contribute to flow regulation and the restoration of natural riverbed morphology (Koehnken et al. 2020; Rentier and Cammeraat 2022), while at the same time posing potential risks of hydrodynamic alteration, erosion, groundwater level decline (Farahani and Bayazidi 2018; Hackney et al. 2020a; Rentier and Cammeraat 2022; Sonak et al. 2006; Padmalal and Maya 2014a), resource scarcity, and saltwater intrusion (Loc et al. 2021; Park et al. 2022). Worldwide, numerous studies have pointed out the consequences of sand extraction exceeding natural thresholds. In China, Luo and co-authors (2007) found that sand dredging in the Pearl River Delta increased channel slope, caused bank instability, and enhanced saltwater intrusion, in addition to benefits such as flood reduction and improved inland navigation (Luo et al. 2007). Similarly, Ashraf and co-authors (2011) warned that extraction exceeding natural replenishment capacity at Bestari Jaya (Malaysia) led to downstream erosion, flow alteration, and increased water turbidity (Ashraf et al. 2011). More recently, Rentier and co-authors (2022) synthesized the multidimensional impacts of sand mining on the physical environment (river widening), biological aspects (biodiversity decline), chemical components (water and soil pollution), and social dimensions (infrastructure damage and labor risks) (Rentier and Cammeraat 2022).

In the Mekong Delta, sand mining has become a critical issue due to increasing construction demand and reduced sediment supply from the upstream Mekong River (Jordan et al. 2019; Kummu et al. 2008; Miyazawa et al. 2008). Unsustainable extraction has created localized scour pits and disrupted flow structures (Anthony et al. 2015; Kim et al. 2020; Brunier et al. 2014; Barman et al. 2018), especially when sediment replenishment is insufficient, leading to uncontrolled expansion of erosion pits (Kondolf 1997; Barman et al. 2019; Padmalal and Maya 2014b; Kim et al. 2020). Bravard and co-authors (2013) estimated that approximately 50 million tons of sand per year are extracted from the Mekong Delta, mainly in Cambodia and Vietnam (Bravard et al. 2013). The study by Gruel and co-authors (2022) showed that during the period 2015–2020, the Tien River (upstream of My Thuan) accounted for 66% of the total sand extraction volume in the region (167.17 million m3), while the Hau River accounted for only 17%. Downstream of My Thuan, there are areas with lower extraction intensity, with an extracted volume of 42.19 million m3, accounting for about 17% of the total reserves. Compared to the Tien River, the Hau River has a lower extraction rate of 44.22 million m3, representing approximately 17% of the total extracted volume (Gruel et al. 2022). The direct consequence is increased riverbank erosion, with more than 665 erosion sites recorded up to 2019, mainly concentrated along the Tien River and the Hau River, with a total affected length exceeding 224 km (Bay 2017 - 2021). Unsustainable sand mining combined with sediment reduction has rapidly lowered riverbed levels. Christopher R. Hackney (2020) pointed out that sand mining activities along the Mekong River currently exceed allowable levels, causing significant changes in river hydrodynamic and morphological processes (Hackney et al. 2020b). Nguyen Nghia Hung and co-authors (2020) indicated that the rate of riverbed lowering in the Mekong Delta during the period 2008–2018 reached up to 15.3 cm per year, which is substantially higher than the rates of land subsidence (1–2.5 cm per year) and sea level rise (Hung et al. 2020). This has altered tidal regimes, increased saltwater intrusion, and threatened freshwater resources. Climate change further exacerbates this situation through seasonal flow alteration, increased droughts, and intensified storms and floods (Bay et al. 2023; Dang and Pokhrel 2024; Vu et al. 2024). Sand mining is one of the contributing factors to riverbed incision, accounting for approximately 2.9% (ranging from 2.6% to 3.6%) of incision in the Tan Chau – My Thuan reach of the Tien River and Vam Kenh. Binh and co-authors (2020) suggested that if sand mining activities across the entire Mekong Delta reach a volume of 7.75 million m3 per year, as mentioned in (Bravard et al. 2013), they could contribute up to 14.8% of the total observed incision volume. It is noteworthy that this percentage could be even higher, as sand mining operators often underreport extraction volumes to reduce associated costs (Bravard et al. 2013). In addition, sand mining in the Mekong Delta is mainly carried out using rudimentary tools such as shovels, involves illegal sand extraction, and the continued practice of excessive mining activities, which together contribute to making the region increasingly difficult to manage (Ng and Park 2021).

Many studies have applied advanced technologies to predict and mitigate risks in the Mekong Delta. Binh and co-authors (2022) simulated the formation of 16 scour holes on the Tien–Hau River system during 2014–2017 and predicted the development of an additional 22 scour holes by 2026 if sediment supply continues to decline. This study focused on identifying and tracking the dynamic evolution of scour holes within the river channel, reflecting their migration and expansion over time. However, sand mining activities in this study were not simulated as a continuous process in time, but were mainly considered indirectly through changes in riverbed morphology and reductions in sediment supply (Binh et al. 2022). Kim and co-authors (2020) modeled the impacts of sand mining on morphological changes and the expansion of scour holes along the Tien River reach flowing through Tan Chau town using the HYDIST–GPUs model, which allows the assessment of time varying impacts of sand mining (Kim et al. 2020). More recently, Thi Huong Vu and co-authors (2025) combined deep learning, satellite imagery, and the Delft3D-FLOW model to assess the impacts of sand mining on riverbed morphology in the Mekong Delta. The impacts of sand mining in this study were primarily represented in the model as erosion pits and static extraction zones, with no temporal variability **(**Vu et al. 2025**)**.

Overall, previous studies have demonstrated the link between sand mining, riverbed erosion, and environmental degradation; however, most numerical models still rely on the assumption of mining pits with fixed shapes and locations. This approach does not fully capture the dynamic nature of sand mining processes, in which dredging activities occur continuously over time and directly interact with sediment transport processes and riverbed morphological evolution (Binh et al. 2022; Gruel et al. 2022; Rentier and Cammeraat 2022; Kim et al. 2020). Based on these considerations, the present study applies the HYDIST model with the integration of a sand mining source function, enabling the simulation of unsustainable sand mining as a dynamic component of the system, and thereby allowing a quantitative assessment of riverbed morphological changes both within mining areas and in river reaches affected by propagated impacts. The study area is the Vam Nao River reach, which plays a key role in conveying large discharges, exhibits strong flow fields and high morphological variability, and is also a zone of concentrated large scale sand mining activities. The application of the HYDIST model at this highly sensitive location enables the assessment not only of local impacts of sand mining at mining sites, but also of propagated effects on the confluence zone and adjacent river reaches, thereby clarifying the relationship between sand mining and channel instability at one of the most important hydrodynamic nodes of the Mekong River system.

2. STUDY AREA

The Vam Nao River, an important watercourse within the Mekong River system, occupies a distinctive geographical position in An Giang Province, Viet Nam. The river functions as a natural hydraulic link between the two main branches, the Tien River and the Hau River, forming a unique hydrological structure within the Mekong Delta (Winemiller et al. 2016). According to reports from the Department of Agriculture and Environment, during the 2019 flood season, high discharges combined with strong currents caused localized bank erosion in several areas of Cho Moi and Nhon My communes (An Giang Provincial Department of Natural Resources and Environment 2021). For this reason, the project “Dredging and river training of the Vam Nao River to mitigate bank erosion in My Hoi Dong commune and Kien An commune, Cho Moi district, An Giang Province”, located along the river reach flowing through Tan Trung commune, Phu Tan district (right bank), and My Hoi Dong and Kien An communes, Cho Moi district (left bank), An Giang Province, was licensed with the objectives of reducing bank erosion and supplying sand for expressway construction projects (An Giang Provincial People’s Committee 2023).

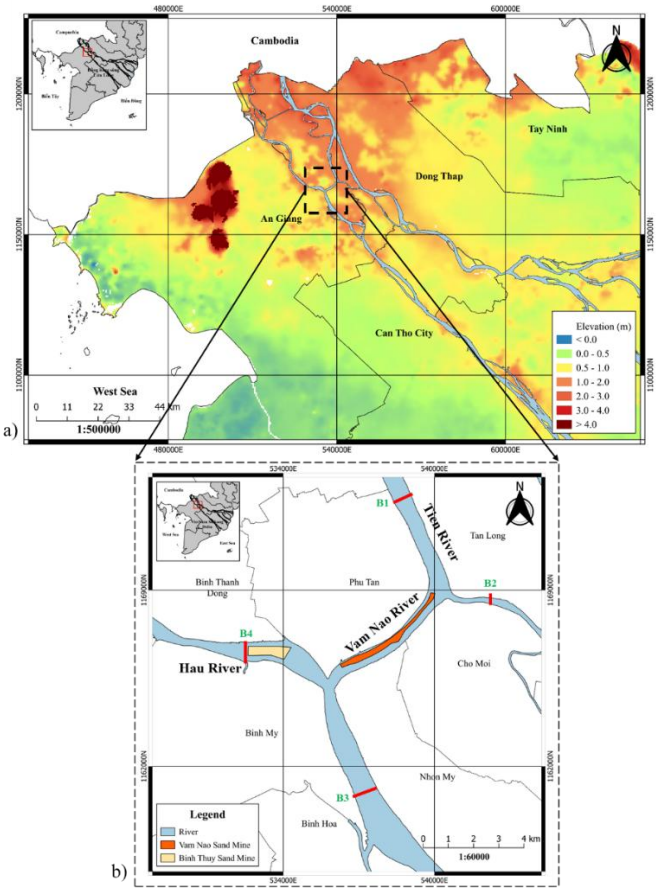

Figure 1 a) Topo DEM in Mekong Delta include the study area (*Minderhoud et al. 2019*) b) Study area

The sand mining site is located along the Vam Nao River, adjacent to Phu Tan commune on the right bank and Cho Moi and Nhon My communes on the left bank in An Giang Province (see Figure 1b). The mining area covers 79.9 ha, with a mining reach length of approximately 4.778 km. The planned extraction period is three years, with an average dredging capacity of 1,200,000 m^3 per year and a maximum allowable bed elevation of −15 m (An Giang Provincial People's Committee 2023).

3. METHODS

3.1. Methodological framework

Figure 2 presents the methodological framework of the study, which consists of four main steps. In Step 1, data preparation, riverbanks were delineated from Google Earth (GE), while riverbed topography was updated using survey data collected in 2022. Hydrological and sediment related data, including discharge (Q), water level (H), and total suspended sediment concentration (TSS), were extracted from the MIKE 11 model and used as input for the HYDIST model. The second step involves the setup of the HYDIST model, comprising two components: the hydrodynamic model and the sediment transport model. The hydrodynamic model provides velocity fields (U, V) and bed shear stress (τ_b), which serve as inputs for sediment transport simulations. This is followed by the model calibration and validation stage, during which simulated results are compared with observed data to assess model reliability. Finally, the validated model is applied to analyze morphological changes under three scenarios: (i) the baseline condition, (ii) sand mining, and (iii) sand mining combined with climate change impacts. These scenarios enable a combined assessment of the effects of anthropogenic activities and climatic factors on the evolution of riverbed morphology.

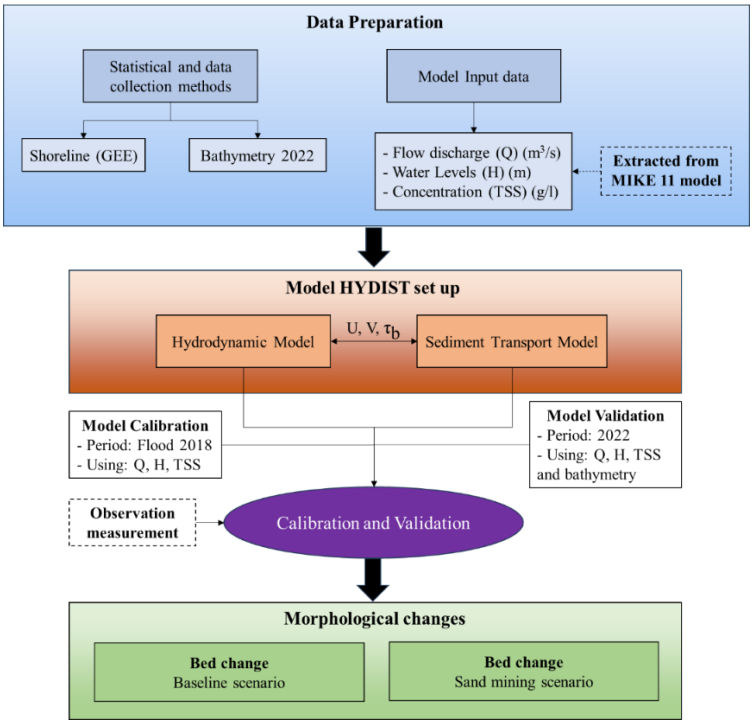

Figure 2 Methodological Framework in this study

3.2. Materials

Boundary data of discharge Q(t) and ς(t) for the years 2018 and 2022 were inherited from the MIKE 11 model developed under the project "Study on identifying causes and mechanisms and proposing technically feasible and economically effective solutions to mitigate erosion and deposition in the river system of the Mekong Delta (KHCN-TNB.DT/14-19/C10)" (Bay 2017 - 2021).

Hourly discharge (Q) and water level (H) data, together with daily suspended sediment concentration (TSS) data for 2018 and 2022 at the Vam Nao station, were collected from the Southern Regional Hydro-Meteorological Center and used for model calibration and validation.

Bathymetric data and information on sand mining sites were obtained from the project "Dredging and river training of the Vam Nao River to mitigate bank erosion in My Hoi Dong commune and Kien An commune, Cho Moi district, An Giang Province" (Department of Science and Technology of An Giang Province 2023).

Grain size distribution data were inherited from the project "Study on identifying causes and mechanisms and proposing technically feasible and economically effective solutions to mitigate erosion and deposition in the river system of the Mekong Delta (KHCN-TNB.DT/14-19/C10)" (Bay 2017 - 2021). Sediments in the study area are non-cohesive sand–silt material, with d50 = 0.05 mm and d90 = 0.1 mm.

3.3. HYDIST model

The HYDIST model is a 2D surface model, in which the Ox and Oy axes represent the longitudinal and transverse directions of the study area, as illustrated in **Error! Reference source not found.**. The model is formulated based on f our governing equations: the depth-averaged Reynolds equations, the continuity equation, the sediment diffusion and transport equation, and the bed evolution continuity equation (Kim et al. 2020).

3.3.1. Reynolds Equation in the *Ox* and *Oy* Directions

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial \varsigma}{\partial x} - Ku\frac{\sqrt{u^2+v^2}}{h+\varsigma} + A\nabla^2 u \qquad (3.1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial \varsigma}{\partial y} - Kv\frac{\sqrt{u^2+v^2}}{h+\varsigma} + A\nabla^2 v \quad (3.2)$$

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial}{\partial x}[(h+\varsigma)u] + \frac{\partial}{\partial y}[(h+\varsigma)v] = 0 \quad (3.3)$$

158 **3.3.2. Suspended Sediment Transport Equation**

$$\frac{\partial C}{\partial t} + \gamma_v\left(u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y}\right) = \frac{1}{H}\frac{\partial}{\partial x}\left(HK_x\frac{\partial C}{\partial x}\right) + \frac{1}{H}\frac{\partial}{\partial y}\left(HK_y\frac{\partial C}{\partial y}\right) + \frac{S}{H} \quad (3.4)$$

159 Where: S is the source term representing the rate of deposition and erosion (m/s). The source term is defined
160 according to the empirical formulation proposed by Van Rijn (Van Rijn 1993):

161 + When the bed shear stress exceeds the critical shear stress for erosion: $\tau_b > \tau_e$, S is an erosion function and S
162 = E:

$$E = \frac{M}{\rho_s}\frac{\tau_b - \tau_e}{\tau_e} \quad (3.5)$$

163 + When the bed shear stress is lower than the critical shear stress for deposition: $\tau b < \tau d$, S is a deposition
164 function and S = D:

$$D = -\omega_{sm}C_b\frac{\tau_d - \tau_b}{\tau_d} \quad (3.6)$$

165 + When $\tau e \geq \tau b \geq \tau d$:

$$S = 0 \quad (3.7)$$

166 **3.3.3. Bed Load Continuity Equation with Sand Mining Component**

$$\frac{\partial h}{\partial t} = \frac{1}{1-\varepsilon_p}\left[(S + S_{sm}) + \frac{\partial}{\partial x}\left(HK_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(HK_y\frac{\partial C}{\partial y}\right) + \frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y}\right] \quad (3.8)$$

167 Where: S_{sm} is the sand mine source and the standing sand mining rate (m/s).

168 The above equations are solved using the finite difference method with the Alternating Direction Implicit (ADI)
169 scheme proposed by Peaceman and Rachfor (Kim et al. 2020).

170 **3.4. Model Performance Asessment**

171 In this study, the quality of model calibration and validation is evaluated using the indicators R^2, NSE, RSR, and
172 PBIAS. Specifically, R^2 represents the degree of linear correlation, NSE evaluates how well the simulated values
173 match the observed data relative to the variance of the observations, RSR reflects the relative magnitude of errors, and
174 PBIAS indicates the tendency of the model to overestimate or underestimate compared with observed data (Moriasi
175 et al. 2015). The indexs R^2, NSE, RSR, and PBIAS are calculated using Eqs. (3.9 – 3.12). The performance rating
176 criteria for these indexs are summarized in Table 1.

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \quad (3.9)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{P})^2} \quad (3.10)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - \bar{P})^2}} \quad (3.11)$$

$$PBIAS\ (\%) = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} P_i} x100 \quad (3.12)$$

177 **Table 1** R^2, RSR, NSE and PBIAS general performance ratings for recommended statistics (*Moriasi et al. 2015*)

	Hydraulics and sediment		
Performance	**R^2**	**NSE**	**RSR**
Very Good	$R^2 > 0{,}80$	$0{,}75 < NSE \leq 1{,}00$	$0 \leq RSR \leq 0{,}50$
Good	$0{,}70 \leq R^2 \leq 0{,}80$	$0{,}65 < NSE \leq 0{,}75$	$0{,}50 \leq RSR \leq 0{,}60$
Satisfactory	$0{,}50 \leq R^2 \leq 0{,}70$	$0{,}50 < NSE \leq 0{,}65$	$0{,}60 \leq RSR \leq 0{,}70$
Unsatisfactory	$R^2 \leq 0{,}50$	$NSE \leq 0{,}50$	$RSR > 0{,}70$
	Morphology		
	PBIAS		
Very Good	$\|PBIAS\| < 10$		
Good	$10 \leq \|PBIAS\| < 15$		
Satisfactory	$15 \leq \|PBIAS\| < 20$		
Unsatisfactory	$\|PBIAS\| > 20$		

178 **4. SET UP MODEL**

179 **4.1. Mesh**

180 The computational mesh for the Vam Nao River reach is a rectilinear grid consisting of 636 × 462 cells, covering both
181 the river channel and land areas. The maximum water depth represented in the mesh is h = 43.45 m, with structure
182 grid spacing of $\Delta x = \Delta y = 20$ m. Sand mining locations are incorporated into the model in the form of a source matrix
183 S_{sm} (i, j) with the same dimensions as the computational grid (see Figure 3b), where S_{sm} (i, j) represents the sand
184 extraction rate at each grid cell (i, j). The sand mining rate at each cell (i, j) is calculated based on field data obtained
185 from the project documentation (Department of Science and Technology of An Giang Province 2023), and is
186 summarized in Table 2. In contrast to the approach adopted by Tran Thi Kim et al. (2020) (Kim et al. 2020), the present
187 study determines the average sand mining rate from actual operating time records and then assumes continuous
188 extraction to assess the impacts of sand mining on riverbed morphology.

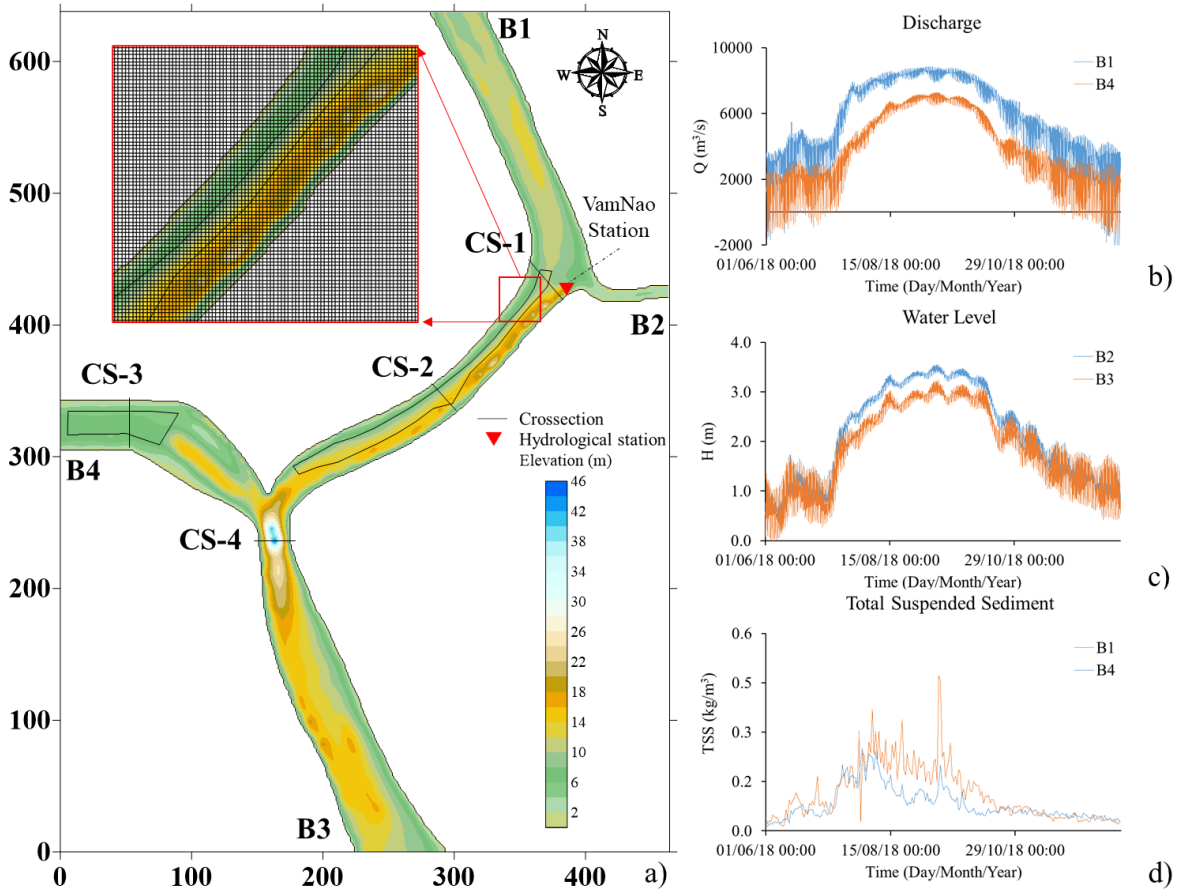

Figure 3 a) Riverbed topography in 2022 and the HYDIST computational mesh; b) discharge data; c) water level; and d) suspended sediment concentration extracted from the MIKE 11 model

Table 2 Average exploitation speed of sand mines

Sand mine	Extractable volume (m^3)	Area (m^2)	Mining rate (m/s)	Working time (hours)	Mine lifetime (years)
Vam Nao	3,461,000	799,000	1.22×10^{-7}	9 hours	3 years
Binh Thuy	4,161,213	614,700	1.87×10^{-7}	9 hours	2 years

4.2. Boundary data and initial condition

4.2.1. Inital conditions

In the model, when computations start at $t_0 = 0$, the hydrodynamic problem is initialized with a static condition over the entire domain. In cases where the simulation is continued from a given time $t = t_1$, the initial conditions consist of the velocity fields u, v (x, y) and the sediment concentration field C (x, y) at time t_1 over the whole computational domain.

4.2.2. Boundaries conditions

Hydrodynamic conditions:

The upstream and left boundaries are prescribed using the discharge time series Q(t) and the velocity distribution along the open boundaries is redistributed according to the following formula:

$$u, v = \left[\frac{Q}{\frac{\sum(h_i^{\frac{5}{3}})}{h_i \Delta x}} h_i^{\frac{5}{3}} \right] \quad (3.13)$$

The downstream and right boundaries are defined using the water level time series z(t).

Sediment transport conditions:

When flow enters the computational domain, the sediment concentration is set to $C = C_o$.

When flow exits the domain, sediment concentration is computed through advective transport, with diffusion neglected, and solved using the method of characteristics (Bay et al. 2019). With this approach, sediment is allowed to enter and leave the computational domain, leading to more accurate simulation results.

Land boundary:

Hydrodynamics conditions: $u_n = 0$

Sediment transport conditions: $\frac{\partial C}{\partial n} = 0$

The Vam Nao station is used for model calibration and validation. This study employs the 2018 flood season and both the dry season and flood season of 2022 for calibration and validation. Input data include discharge Q(t), water level ς(t) and sediment concentration C(t) for the years 2018 and 2022, as shown in Figure 3b, c, d.

4.3. Model parameter

The model parameters used in this study are presented in Table 3. In which, the median grain size (d50) and the characteristic grain size (d90) were determined from sediment samples measured in situ in the study area (Bay 2017 - 2021). Other parameters such as porosity, particle density, kinematic viscosity, and critical deposition–erosion shear stress were inherited from previous studies and adjusted during the model calibration process (Binh et al. 2022; Thanh et al. 2017; Hung et al. 2014).

Table 3 Parameter of the HYDIST model

Parameters	**Value**
Time step Δt	2 (s)
Roughness coefficient n	0.015 – 0.027
Particle porosity ε_p	0,375
Median particle diameter (d_{50}) 50%	$5x10^{-5}$ (m)
Particle diameter (d_{90}) 90%	$1x10^{-4}$ (m)
Kinematic viscosity (ν)	$1,01x10^{-6}$ (m^2/s)
Particle density (ρ_s)	2600 (kg/m^3)
Erosion coefficient M	$1x10^{-6}$ ($kg/m^2/s$)
Critical deposition shear stress τ_d	0,06 (N/m^2)
Critical erosion shear stress τ_e	0,35 (N/m^2)

4.4. Scenarios

In this study, simulation scenarios were developed to comprehensively evaluate the factors governing riverbed morphological changes in 2022. Based on Decision No. 1541/QD-UBND approving the list of river sand mineral areas serving infrastructure development and socio-economic projects in the Mekong Delta, the Vam Nao river reach was

identified as one of the important sand mining sites of An Giang province (An Giang Provincial People's Committee 2023). However, this area simultaneously exhibits complex hydraulic–morphological conditions and frequently experiences severe bank erosion, raising concerns that sand mining activities may increase the risk of channel instability. On this basis, the study established two simulation scenarios to analyze and evaluate the riverbed morphological evolution at Vam Nao. In which, scenario KB-1 represents the existing condition without sand mining and serves as the reference scenario, while scenario KB-2 incorporates the impacts of sand mining activities to quantify the level of influence on channel morphology changes, particularly the variation of scour holes at the confluence of the Vam Nao River reach.

Scenario name	Description
SC-1	Simulation of riverbed evolution in 2022 under existing conditions (no sand mining).
SC-2	Simulation of riverbed evolution in 2022 with the Vam Nao sand mine and the Binh Thuy sand mine.

5. RESULTS

5.1. Calibration and validation model

The model was calibrated and validated using data from the flood season in 2018, and the dry season and flood season in 2022. This study focused on simulating one flood season year (from June to December) in order to reduce simulation time, since more than 90% of suspended sediment load is transported during the flood season (Binh et al. 2020). Measured data at the Vam Nao station were used for model calibration and validation, including discharge, water level, suspended sediment, and three cross sections of the Vam Nao River. In sequence, the hydraulic model was first calibrated by adjusting the roughness coefficient. Subsequently, the bed sediment transport model was further calibrated through the erosion coefficient M, critical deposition shear stress τ_d and critical erosion shear stress τ_e. The calibration and validation results of the parameters met acceptable criteria, specifically the roughness coefficient n ranged from 0,0145 – 0,0275 $s/m^{1/3}$, the erosion coefficient M = $2x10^{-5}$ ($kg/s.m^2$), the critical deposition shear stress τ_d = 0,04 (N/m^2) and the critical erosion shear stress τ_e = 0,15 (N/m^2). The values of R^2, RMSE, NSE và PBIAS (Table 4) indicate that the HYDIST model was calibrated and validated in a reliable manner. Furthermore, the simulated discharge, water level, TSS, and riverbed depth are consistent with the corresponding measured data (Figure 4 and Figure 5) (Moriasi et al. 2015).

Table 4 Evaluation of the model performance

Values		Model Calibration	Model Validation				
		Flood 2018	Dry 2022	Flood 2022	CS - 1	CS - 2	CS - 3
Discharge	R^2	0.88	0.84	0.70			
	NSE	0.86	0.83	0.55			
	RSR	0.36	0.40	0.66			
Water Level	R^2	0.88	0.91	0.91			
	NSE	0.81	0.90	0.90			
	RSR	0.37	0.31	0.31			
TSS	R^2	0.61	0.69	0.55			
	NSE	0.53	0.51	0.54			
	RSR	0.66	0.67	0.65			
Cross-section	PBIAS				13.53	11.35	20.02

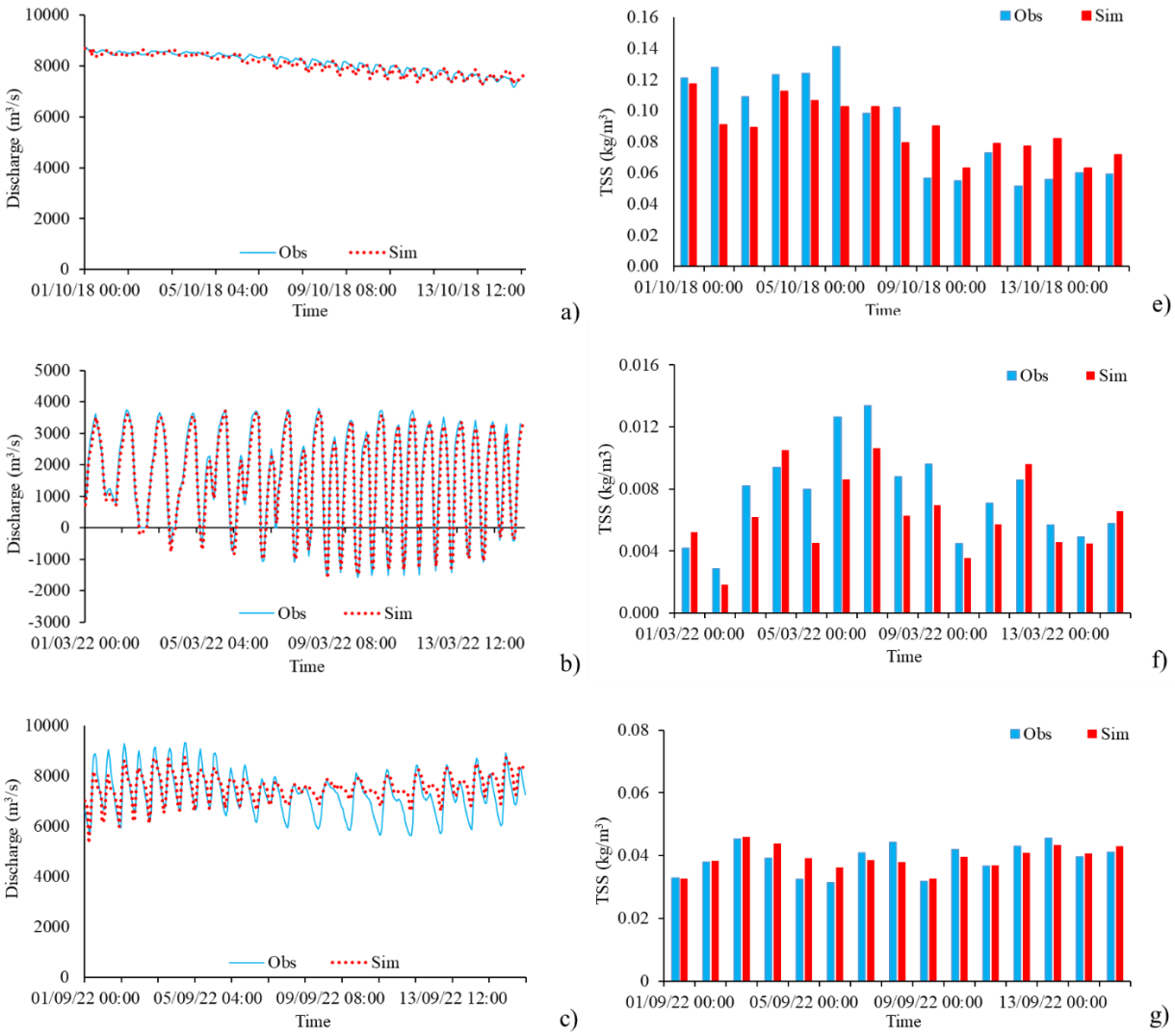

Figure 4 Calibration and validation of discharge and suspended sediment

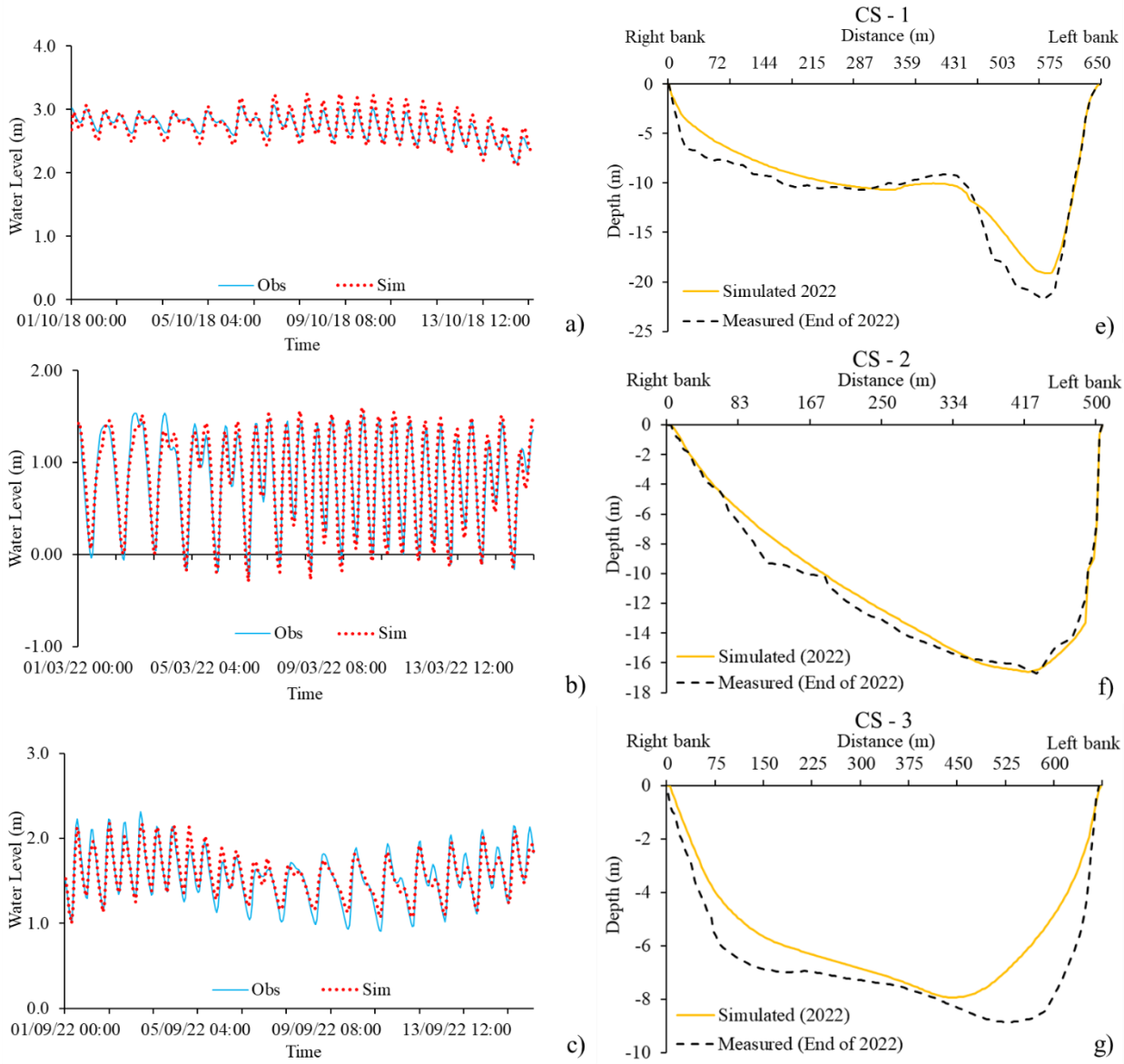

Figure 5 Calibration and validation of water level and cross sections

5.2. Hydrodynamic in the Vam Nao River confluence

The hydrodynamic simulation results at the flood peak at 20:00 on 01/10/2022 are presented in Figure 6, illustrating the spatial distribution of the flow velocity field in the study area and indicating pronounced heterogeneity in hydrodynamic conditions. Specifically, the Vam Nao River reach plays the role of a water transfer pathway from the Tien River to the Hau River, characterized by a high velocity flow field. In Zone 1, the flow within the Vam Nao channel reaches a maximum velocity of up to 3.0 m/s at location 1 (concave bank area) and ranges from 2.0 – 2.5 m/s at locations 2 and 3. The velocity vectors in this area are highly concentrated and exhibit large magnitudes, reflecting the strong kinetic energy of flow transferred from the Tien River to the Hau River.

In contrast, in Zone 2 located in the upstream reach of the Hau River, the velocity field records significantly lower values, ranging only from 0.25 – 0.5 m/s at location 4 near the riverbank and approximately 1.0 m/s at location 5 in the middle of the channel. The large disparity in velocity fields between the Vam Nao flow and the upstream flow of the Hau River creates a complex hydraulic interaction zone at the river confluence (Zone 3). At this location

(location 6), the confluence leads to a localized increase in flow velocity (reaching 2.5 m/s), generating turbulent flows that are capable of inducing bank failure, deep scour, and severe changes in channel morphology.

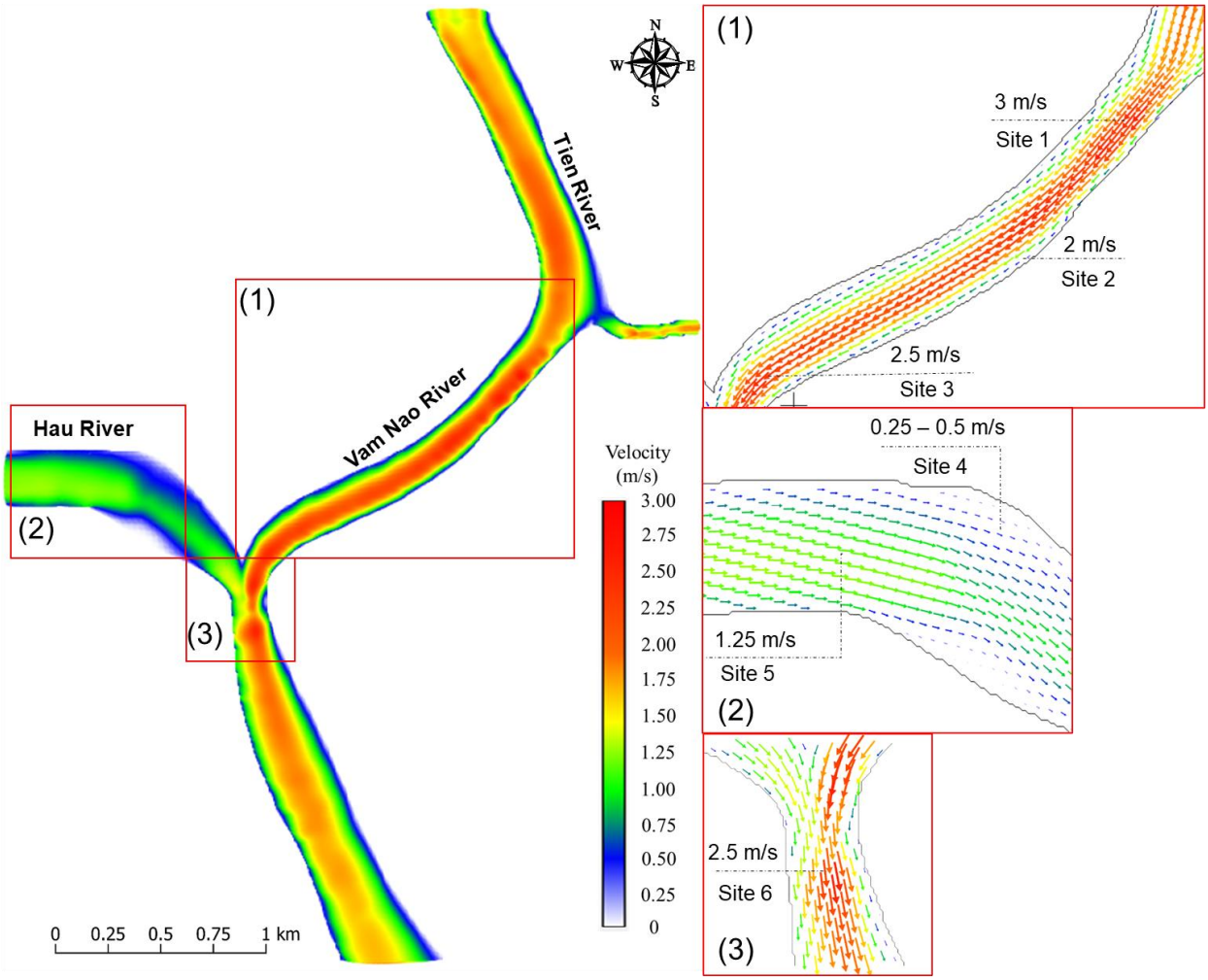

Figure 6 Velocity field at flood peak at 20:00 on 01/10/2022

5.3. Bed change in Vam Nao with sand mining and without sand mining

Figure 7 shows a clear contrast in bed elevation evolution between the two scenarios. Under SC2, sand mining activities markedly intensify erosion compared to the existing condition, with deep scour zones forming directly within the mining areas in both Zone 1 and Zone 2. Due to changes in the velocity field after the flow passes through the mining sites in the Hau River and the Vam Nao River, erosion is not confined to the extraction locations but propagates downstream, most clearly expressed in Zone 3, corresponding to the Hau–Vam Nao confluence. In this zone, erosion develops asymmetrically toward the right bank and exhibits substantially greater intensity under scenario SC2. In Zone 1, the baseline scenario (SC1) indicates that this river reach is already dominated by erosional conditions, with erosion accounting for 72.9% of the total bed change (equivalent to 426,153 m^3). However, under the mining scenario (SC2), sediment imbalance becomes more severe. The data indicate a pronounced reduction in deposition, decreasing from 27.1% (158,561.87 m^3) to only 12.9% (124,180.10 m^3), while erosion increases sharply, accounting for 87.1% of the total bed change. Notably, the total volume of material lost under SC2 reaches approximately 840,849.06 m^3, nearly doubling (about 1.97 times) that of the baseline scenario, which is only 426,152.71 m^3.

In contrast to the strong hydraulic regime of the Vam Nao River, the Hau River area (Zone 2) under natural conditions exhibits characteristics of a sediment deposition environment. Specifically, in the baseline scenario (SC1),

this area functions as a sediment trap, with deposition overwhelmingly dominant (83.77%, equivalent to 256,993.19 m^3), while erosion remains negligible. However, sand mining activities under SC2 completely reverse this bed evolution trend. From a depositional state, the area shifts to a strongly erosional regime, with erosion becoming dominant at 68.81% (reaching 416,930.3 m^3). Remarkably, the erosion volume in this scenario increases by a factor of 8.4 compared to natural conditions (49,783 m^3).

The river confluence area (Zone 3), a hydraulic junction where complex flow interactions occur between the Tien River (via the Vam Nao reach) and the Hau River, exhibits a high sensitivity to upstream alterations. Under the baseline scenario (SC1), this zone maintains a state in which erosion is dominant, accounting for approximately 58.63% (149,761.11 m^3) of the total morphological change due to the presence of a naturally developed deep scour hole, while still sustaining a substantial proportion of deposition at about 41.37% (105,673.38 m^3). However, scenario SC2 alters both the dynamic processes and the morphological behavior of the area. The results indicate a severe reduction in deposition, decreasing by 30.2% in volume compared to SC1, while erosion intensifies to represent 69.56% of the total morphological change. The increase in total erosion volume (rising by about 12.5% to reach 168,435 m^3) in Zone 3 provides clear evidence of a propagating impact. Upstream dredging activities in Zones 1 and 2 retain a large proportion of bed sediment, leading to a condition of sediment starvation at the river confluence. As a consequence, the flow in this already complex interaction zone is forced to increase its erosive energy locally to compensate for the material deficit, thereby elevating the risk of bank instability and further expansion of scour holes. This finding confirms that localized dredging interventions can induce adverse morphological effects that propagate downstream, threatening the stability of river training structures and riverbanks at vulnerable locations.

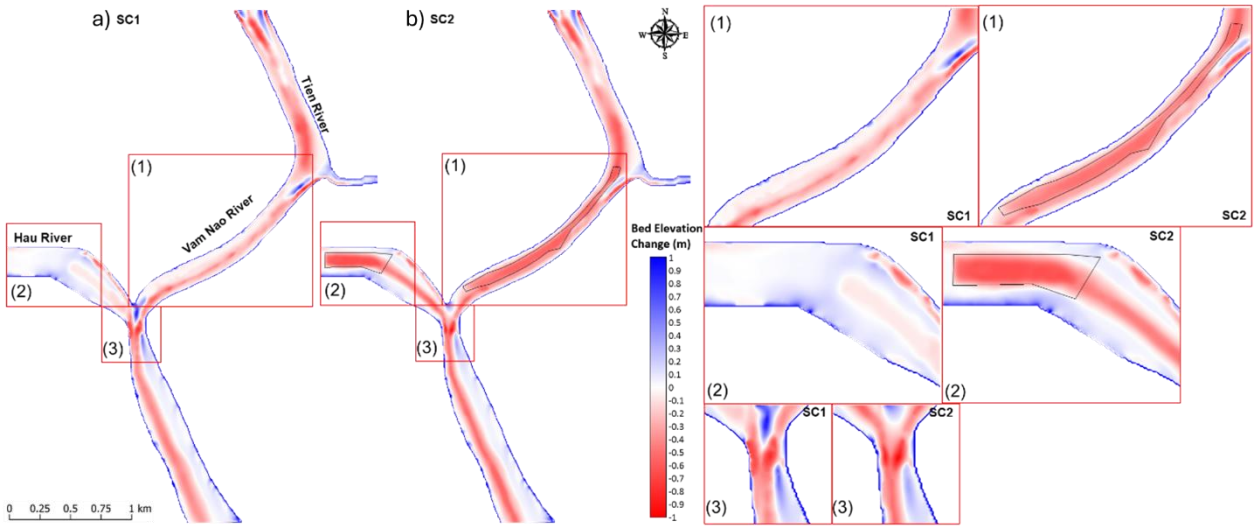

Figure 7 Comparison of bed layer thickness under a) no sand mining and b) sand mining scenarios

Figure 8c-f presents a comparison between the simulated bed topography under the two scenarios and the cross sections measured at the end of 2022 at four locations, CS-1, CS-2, CS-3 and CS-4. Overall, the model reproduces the general channel trends reasonably well, particularly the variation in depth toward the thalweg and the asymmetric geometric form governed by flow concentration. At CS-1 (Figure 8c), erosion is concentrated along the left bank in both scenarios; however, the sand mining scenario exhibits deeper scour in the reach from 144–359 m and a noticeable shift of the erosional zone toward the channel center The simulated results are consistent in trend with the measured bed topography in 2022. At CS-2 (Figure 8d), erosion is focused in the central part of the channel, with depths under the sand mining scenario exceeding those of the no-mining scenario by 0.8–1.0 m. At CS-3 (Figure 8e), the simulation successfully captures the deepening trend toward the right bank and the asymmetric channel shape, with maximum depths ranging from –7.2 to –7.8 m compared to the measured value of –10.5 m, indicating that the model adequately represents the overall direction of morphological change. The CS-4 cross section clearly illustrates bed lowering

within the scour hole area under the influence of dredging activities, while the asymmetric V-shaped channel form is maintained (Figure 8f).

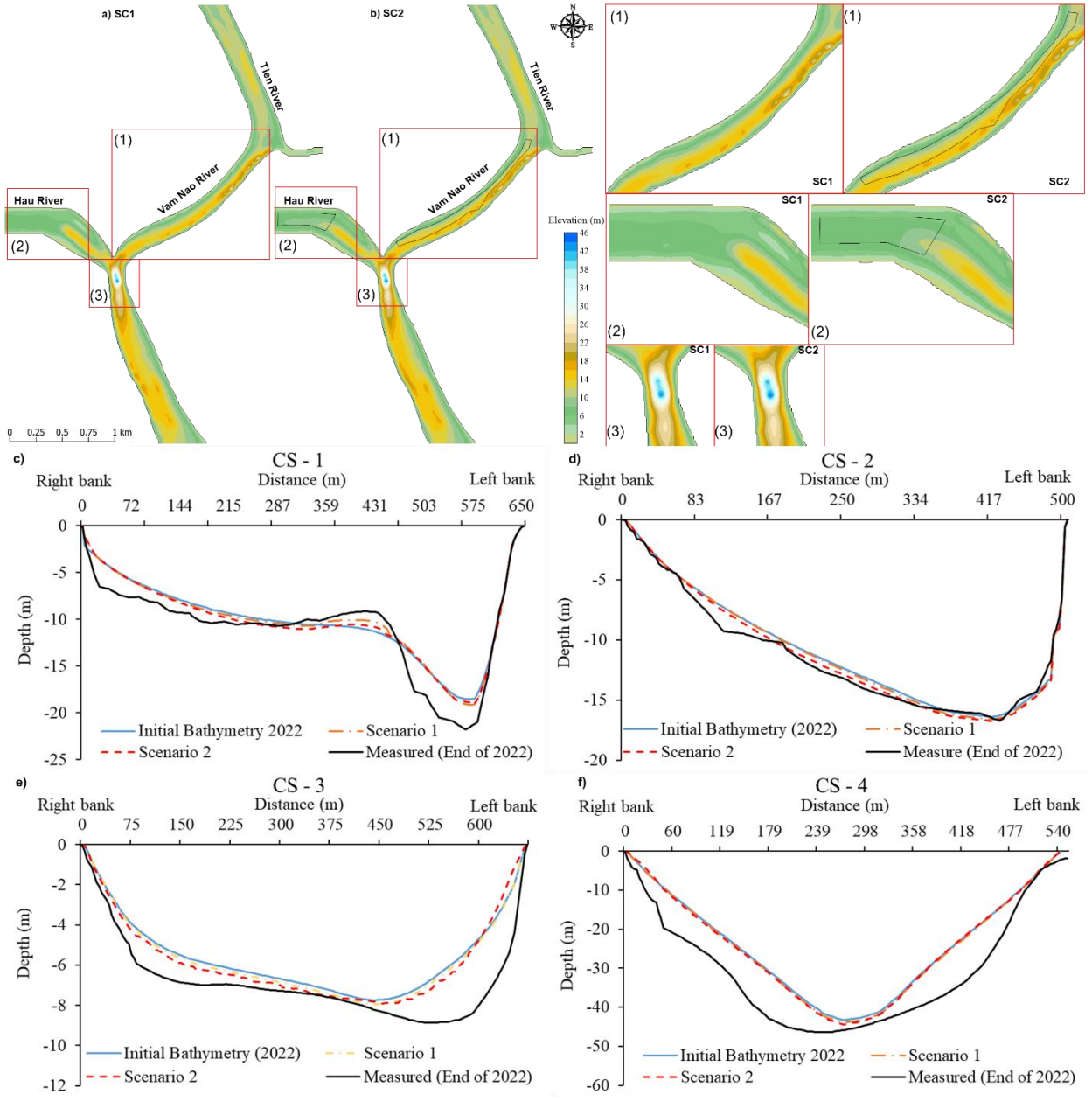

Figure 8 Comparison of bed topography evolution under a) no sand mining, b) sand mining scenarios and four crossection (c-f)

Specifically, relative to the baseline scenario (SC1), the maximum bed elevation in the dredging scenario (SC2) is further lowered by approximately 2.0 m, reaching a depth of about –45 m compared to –43 m under existing conditions, directly reflecting anthropogenic intervention in the channel profile. Overall, sand mining distinctly alters the spatial distribution of erosion and deposition, promotes the development of new flow paths, and reduces direct impacts on the riverbanks. The simulation results obtained in this study show strong agreement with recent field observations reported by Vu et al. (2025) (Vu et al. 2025). Based on measured data, these authors documented a trend of deepening and downstream expansion of the scour hole at the river confluence. The successful reproduction of this

morphological evolution by the model not only reinforces the reliability of the simulation scenarios but also provides quantitative evidence supporting the conclusion that sand mining activities are a key driver intensifying scour development at the confluence area.

6. DISCUSSION

The simulation results for the Vam Nao River reach demonstrate that sand mining activities exert a pronounced influence on channel morphological evolution. A comparison between the scenarios with and without sand mining indicates that, in the Vam Nao area (Zone 1), the proportion of deposition decreases from 27.1% to 12.9% under the mining scenario, while erosion accounts for as much as 87.1% of the total morphological change. Notably, in the Hau River reach (Zone 2), which is naturally characterized by depositional conditions, erosion increases abruptly, with the total eroded volume approximately 8.4 times greater than that under the no-mining scenario. In the Vam Nao–Hau River confluence area (Zone 3), deposition volume decreases by 30.2% relative to the condition without sand mining, while erosion represents 69.56% of the total morphological change, clearly indicating a downstream propagating impact of upstream sand extraction.

These findings are consistent with general trends reported in numerous international studies on in-channel sand mining. Global syntheses have consistently identified sand extraction as a major driver of riverbed lowering, channel widening, and increased bank instability (Rentier and Cammeraat 2022; Binh et al. 2022; Kim et al. 2020; Padmalal and Maya 2014a). In particular, studies conducted within the Mekong River basin indicate that current sand extraction volumes far exceed the natural replenishment capacity of the system, resulting in widespread sediment deficits (Gruel et al. 2022; Hackney et al. 2020a). This context explains why, in the present study, although mining areas occupy only a limited portion of the channel, their morphological impacts extend downstream to the confluence reach.

The results of this paper also show strong agreement with previous field-based and remote sensing studies conducted in the Mekong Delta, which have documented progressive riverbed deepening, expansion of scour holes, and temporal shifts of the thalweg in river reaches heavily affected by sand mining(Vu et al. 2025; Binh et al. 2022).

When compared with detailed modeling and observational studies conducted on river reaches affected by sand mining, the magnitudes of local scour at Vam Nao fall within a comparable range but exhibit higher intensity. Kim et al. (2020) reported riverbed lowering rates of 0.6 to 1.2 m/year along reaches of the Tien River directly influenced by sand mining (Kim et al. 2020). In the present study, results at cross section CS-2 indicate that bed depth under the sand mining scenario exceeds that of the no-mining scenario by 0.8–1.0 m within only one simulated year, while in the deep scour area (CS-4), the riverbed elevation decreases by an additional 2.0 m (from about −43 m to nearly −45 m). This indicates that erosion intensity at Vam Nao is generally comparable to that observed along the segment of Tien River flowing Tan Chau, and at certain scour locations it even exceeds it. Nguyen Nghia Hung et al. (2020) reported an average riverbed lowering rate across the Mekong Delta of approximately 15.3 cm/year during the period 2008–2018 (Hung et al. 2020)., while Hackney et al. (2020) estimated a rate of about 0.13 m/year (Hackney et al. 2020a) c The study by Christopher R. Hackney et al. (2020) further demonstrated that unsustainable sand mining can deepen channels and enlarge scour holes with amplitudes ranging from 1.5 to 3.0 m in sensitive reaches of the Mekong River. The local scour depths observed at Vam Nao, particularly in the confluence area, lie within this range, indicating that sand mining impacts at this site are not minor or isolated phenomena but belong to the category of high impact cases documented across the region (Hackney et al. 2020a).

The study by (Vu et al. 2025) documented significant riverbed incision along the Hau River, with maximum annual net erosion volumes reaching 29.48 million m^3/year and average erosion rates of up to 0.82 m/year. In addition, excessive sand mining activities resulted in the formation of 23 scour holes with depths of up to 11 m and caused deepening of the main navigation channel (thalweg) at rates reaching −1.18 m/year during the period 2014–2023. These findings are consistent with the quantitative results obtained for Vam Nao, where sand mining not only intensifies erosion at the extraction sites but also leads to a pronounced reduction in deposition (a decrease of 30.2%) and an increase in downstream propagating erosion (168,435 m^3 within one year) at the confluence area, one of the most critical hydrodynamic nodes of the Mekong River system.

Quantifying erosion and deposition volumes demonstrates that sand mining not only exacerbates erosion at extraction sites but also substantially alters the morphological mechanisms of river reaches that are naturally predisposed to deposition. The impact mechanism observed in this study is consistent with the concept of "hungry water," which has been widely discussed in international literature (Hackney et al. 2020a; Brunier et al. 2014; Kondolf 1997). When bed sediment is removed by mining activities, the flow becomes sediment-deficient, thereby increasing its capacity to erode the channel bed and banks downstream in order to compensate for the sediment shortfall. In the case of the Vam Nao River, sediment depletion caused by mining in Zones 1 and 2 enhances erosive energy at the confluence area (Zone 3), where the flow field is already complex and characterized by high velocities. This explains why the confluence exhibits a particularly high sensitivity to upstream anthropogenic interventions. Compared with many previous modeling studies worldwide, which often assume fixed mining pits or consider morphological responses only over long time intervals, the present study demonstrates that representing sand mining as a continuous, time dependent process provides clearer insight into the dynamic nature of riverbed evolution. The results indicate that within only one year of simulation, morphological changes are already sufficient to disrupt sediment balance along several river reaches, especially at the confluence. This suggests that if sand extraction persists over multiple consecutive years, the risk of channel instability and riverbank failure is likely to increase substantially.

7. CONCLUSION

The simulation results demonstrate that sand mining markedly intensifies erosion and disrupts the natural sediment balance. In the Vam Nao River reach (Zone 1), the proportion of deposition decreases from 27.1% to 12.9%, while erosion increases sharply, accounting for 87.1% of the total morphological change. This reflects a clear shift from a relatively balanced erosion–deposition state toward an erosion dominated regime under the influence of sand mining.

In the Hau River reach (Zone 2), which under natural conditions functions as a sediment depositional environment with deposition accounting for up to 83.77%, mining activities completely reverse the prevailing morphological processes. The total erosion volume under the mining scenario reaches 416,930 m^3, approximately 8.4 times greater than that observed in the no-mining scenario.

The most pronounced effects are observed at the Vam Nao–Hau River confluence (Zone 3), where the downstream propagating impacts of upstream sand mining are clearly expressed. Under the mining scenario, deposition volume in this area decreases by 30.2%, while erosion increases to 69.56% of the total morphological change. Sediment starvation resulting from sediment being trapped at mining sites forces the flow at the confluence to increase its local erosive energy, thereby enlarging and deepening existing scour holes and increasing the risk of riverbank instability.

Nevertheless, this study is subject to several limitations. First, the model considers sand mining activities based only on licensed extraction data and does not account for illegal or unreported mining, which is believed to be widespread in the Mekong Delta and may substantially intensify actual erosion rates. Second, the study does not fully incorporate the effects of climate change, including alterations in flow regimes, sea level rise, and reductions in upstream sediment supply, all of which could further exacerbate long term morphological instability.

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AUTHOR CONTRIBUTIONS

Conceptualization: T.T.K and N.D.Q.H; methodology: T.T.K; software: T.T.K, and N.D.Q.H; writing—original draft preparation: T.T.K and N.D.Q.H; writing—review and editing: T.T.K; visualization: T.T.K and N.D.Q.H;. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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