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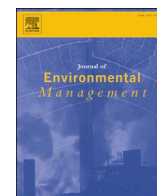
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Discussion

Recurrence interval of riverbed sand mining hotspots in the Mekong delta: Potential indications of unsustainable replenishment rates

Rachel Yu San Lau^a, Edward Park^{a,*}, Yu Qing Koh^a, Dung Duc Tran^{a,b}, Sameh A. Kantoush^c, Doan Van Binh^d, Ho Huu Loc^e

^a National Institute of Education, Earth Observatory of Singapore and Asian School of the Environment, Nanyang Technological University, Singapore

^b Center of Water Management and Climate Change, Institute for Environment and Resources, Vietnam National University Ho Chi Minh City, Ho Chi Minh City, Viet Nam

^c Disaster Prevention Research Institute, Kyoto University, Japan

^d Faculty of Engineering, Vietnamese-German University, Viet Nam

^e Water Systems and Global Change Group, Wageningen University and Research, Wageningen, the Netherlands

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ABSTRACT

Rampant and illegal river sand mining in the Vietnamese Mekong Delta (VMD) has led to substantial sediment losses and bank erosion. However, regulation of this issue remains a significant challenge due to insufficient monitoring and enforcement efforts, partly attributed to limited data and technology. To support an improved monitoring system in the VMD, this study investigates the spatiotemporal changes in sand mining hotspots and their underlying drivers. The recurrence intervals of sand mining boats were assessed from 2014 to 2020 using Sentinel-1A, and its association with riverbed incisions were examined from bathymetry field surveys between 2017 and 2020. Our results attest to sand mining intensification from 2015 to 2020, particularly in the upstream section of the VMD, where 70% of the activity was recorded. Not only was there an apparent increase in sand mining hotspots by 32.4%, but most hotspots recorded a recurrence interval of 2 years. This potentially indicates a minimal timeframe of sediment replenishment before the same locations become economically viable for further sand extraction. Additionally, a correlation was detected between sand mining hotspots and significant riverbed incisions, although the lack of spatial overlaps in some regions suggests other upstream influences like bank collapse and river damming. Our study, through the meticulous assessment of sand mining boat movement and river bathymetry data, ultimately sheds light on the potentially unsustainable scale of sand mining activities in the VMD. It aims to support informed decision-making and effective regulations that tackle excessive sand extraction amid the dynamic environmental challenges we face, while offering valuable insights to similar deltas worldwide.

1. Introduction

Sand, a finite and invaluable resource found in riverine or marine environments, has become one of the most extracted natural materials due to rapid urbanization and development (UNEP, 2019). With its usage spanning across construction, land reclamation, glass production, electronics, and aeronautics, our current consumption of sand is already double the volume produced naturally (Ludacer, 2018). The demand for sand is projected to escalate, reaching an estimated 82 million tons by 2060 (Fritts, 2019), which could deplete global sand resources (Sverdrup et al., 2017). Alongside sand scarcity and increasing demand,

accelerated sand mining has resulted in widespread adverse physical, ecological, and social impacts (WWF, 2018; UNEP, 2019). In the physical environment, not only does the decrease in sediment supply due to sand mining increase erosion along the river (Anthony et al., 2015; Rentier and Cammeraat, 2022), but continued incisions lower the riverbed and undercut riverbanks. The riverbank slopes steepen as a result, making them less stable and prone to eventual bank collapse that can threaten local infrastructure and riparian settlements (Hackney et al., 2020). Ecologically, riverbed instability leads to habitat loss and cascading impacts along the food chain, eventually culminating in the depletion of essential ecosystem services (Torres et al., 2017; Anh and

* Corresponding author.

E-mail address: edward.park@nie.edu.sg (E. Park).

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Schneider, 2020). For agrarian communities reliant on the river for food security, reduced fish populations and lowered groundwater tables related to sand mining exacerbate the loss of agricultural land and productivity (Rentier and Cammeraat, 2022).

Within Southeast Asia (SEA), riverbed sand mining also poses a critical socio-environmental challenge (Lamb et al., 2019). Notably, the Vietnamese Mekong Delta (VMD), one of Asia's largest deltas, has faced increasingly detrimental impacts since sand mining operations began in the 1980s (Bravard et al., 2013; Liu et al., 2017). Unrestrained sand extraction in the VMD, fueled by escalating national construction demands, is compounded by illegal sand mining activities that evade monitoring by local authorities (Dung, 2011; Yuen et al., 2024a). These monitoring efforts are especially challenging in the VMD due to decentralized licensing with poor inter-provincial communication, making tracking operations difficult beyond political boundaries (Schiappacasse et al., 2019). Manpower shortages and technological limitations also hinder on-site monitoring and result in underreported data on sand mining budgets (Gruel et al., 2022). Consequently, the environmental, social, and economic sustainability of the delta is compromised. At a local level, degradation of the environment, through air pollution and habitat destruction, disrupts the livelihoods of local communities who depend on fisheries and agriculture (Tay et al., 2022; Tran et al., 2023). On a broader scale, agricultural and fishery losses in the VMD have severe repercussions on the economy of SEA given its crucial role in maintaining both national and regional food security (The Anh et al., 2020). The severity of the situation, therefore, emphasizes the urgent need for more regulated sand mining practices, which first necessitates a thorough understanding of the spatiotemporal dynamics of sand mining boat activities across the entire VMD.

However, no studies to date have investigated the evolving patterns of sand mining activities, identified hotspot regions within the delta, or delved into a comprehensive analysis of sand mining dynamics. Instead, current literature on sand mining in the region is largely focused on sand extraction quantification and its impacts on the delta's geomorphology, hydrodynamics, and sediment loads. Bravard et al. (2013), Brunier et al. (2014), and Jordan et al. (2019), for instance, provided estimates of sand extraction volumes based on bathymetry surveys or reported statistics. This quantification method was further improved in subsequent studies by Gruel et al. (2022) and Kumar et al. (2023), which incorporated remote sensing analysis to detect sand mining boats and expanded their investigations to cover the entire VMD. In terms of studying the impacts of sand mining, Eslami et al. (2019), Park et al. (2020), Binh et al. (2020a) analyzed the sediment and hydrological changes related to mining activities, while Lau et al. (2023) and Hackney et al. (2020) examined the influence of increased extraction on the riverbed and riverbanks. Though these studies are essential to our understanding of sand mining activities in the region, there is still a notable gap in quantitative research on the dynamics of sand mining boats in the delta. Understanding this is crucial as it serves as a key indicator of sand mining intensity, enabling evaluations to be made on the sustainability of existing extraction rates. Given the prevalence of illegal sand mining practices in the VMD (Yuen et al., 2024a), this lack of understanding hampers the effective management of excessive and illegal sand mining that is necessary to ensure future sand sustainability in the region (Tuyen, 2022).

Our study, thus, seeks to explicitly assess the movement of sand mining activities between 2014 and 2020, across the two main rivers of the VMD, Tien (Mekong) and Hau (Bassac). Patterns and distribution of sand mining activities were identified, "hotspots" were pinpointed, and the frequency of recurrence (or recurrence interval) was quantified. Through these, we quantify sediment replenishment rates to determine the sustainability of the sand mining industry in the study area. Our methodology combines both satellite data and remote sensing techniques provided by Gruel et al. (2022) and bathymetry data by Lau et al. (2023). Along with bathymetry information, the relationship between hotspot activity and localized river incision was evaluated. This detailed

analysis goes beyond merely identifying sand mining hotspots. Our research uniquely focuses on tracking the frequency and locations of boat revisitations to specific hotspots, providing a dynamic and temporally nuanced understanding of sand mining activities. Consequently, this offers invaluable insights into sediment replenishment rates in the delta and serves as an innovative perspective on the sustainability of sand extraction practices in the region. Additionally, the integrated application of boat density information from remote sensing and riverbed morphological data from field surveys represents a novel methodological adoption. This approach is replicable and applicable to future management efforts, providing a valuable tool for effectively managing excessive, particularly illegal, sand mining. Such insights are essential for informed decision-making on sand resource management in the VMD and similar regions globally.

2. Data and methods

2.1. Study area

As the third-largest delta worldwide, the Vietnamese Mekong Delta (VMD) spans an expansive 40,000 km², encompassing 13 provinces in southwestern Vietnam (Fig. 1). The channel itself covers an area of approximately 875 km², with our study area focusing on about 700 km² of it. In the VMD, the channel is split into the Hau and Tien branches, joined by the Vam Nao River in the An Giang Province. The hydrological regime varies seasonally, with a distinct dry season between November to May, and a wet season between June to October that accounts for 75%–90% of the total annual discharge (Brunier et al., 2014; Gruel et al., 2022). This natural seasonal variation in discharge, alongside fine sediment flux, is the backbone of the VMD's agricultural productivity and food security. Upstream damming and sand mining, among other causes, have significantly impacted suspended sediment loads in the VMD (Binh et al., 2020b; Jordan et al., 2020). Recent estimates reflect an annual sediment supply of 43.1 Mt/yr from 2012 to 2015 (Binh et al., 2020b), a 75% decrease from the 1990s. The decreased sediment flux has led to increased incision in riverbeds, bank erosion, and coastline retreats (Anthony et al., 2015; Binh et al., 2020b).

2.2. Sand mining hotspots and recurrence interval analysis

Our research methodology has two distinct phases, as illustrated in Fig. 2. The first phase involves the identification of sand mining hotspots along the Tien and the Hau Rivers, and the estimation of their recurrence intervals. In the second phase, we assess the shifting patterns and depletion rates of several distinct hotspots.

In the first phase, the recurrence interval of sand mining hotspots was calculated based on the boat density map processing method by Gruel et al. (2022). This method follows the same boat classification system to identify sand mining boats in the VMD, facilitating hotspot localization and the estimation of sand extraction. Utilizing Google Earth images from 2019 to 2020 along the Tien River, supplemented by field surveys conducted from 2020 to 2021 and Sentinel-1A satellite imagery, Gruel et al. (2022) identified four types of boat: barges with cranes (BC) for sand extraction; exclusive sand transport barges (BT); motorized blue boats (BB) capable of transporting various materials; and others (OT) involved in pushing or pulling BT or non-sand mining commercial vessels. Only BCs are considered in the analysis. Since BCs typically exhibited a discernible pattern and were often surrounded by boats engaged in sand transportation, a location with BC is likely associated with a high concentration of sand mining boats and can be classified as a "hotspot".

Gruel et al. (2022) processed Sentinel-1A satellite data and Google Earth images from 2014 to 2020 to locate BCs and calculate cumulative and annual BC observations. The use of Sentinel-1 radar images (SAR) was critical for consistently determining sand dredger locations, as these images are immune to cloud cover, atmospheric phenomena, and sun

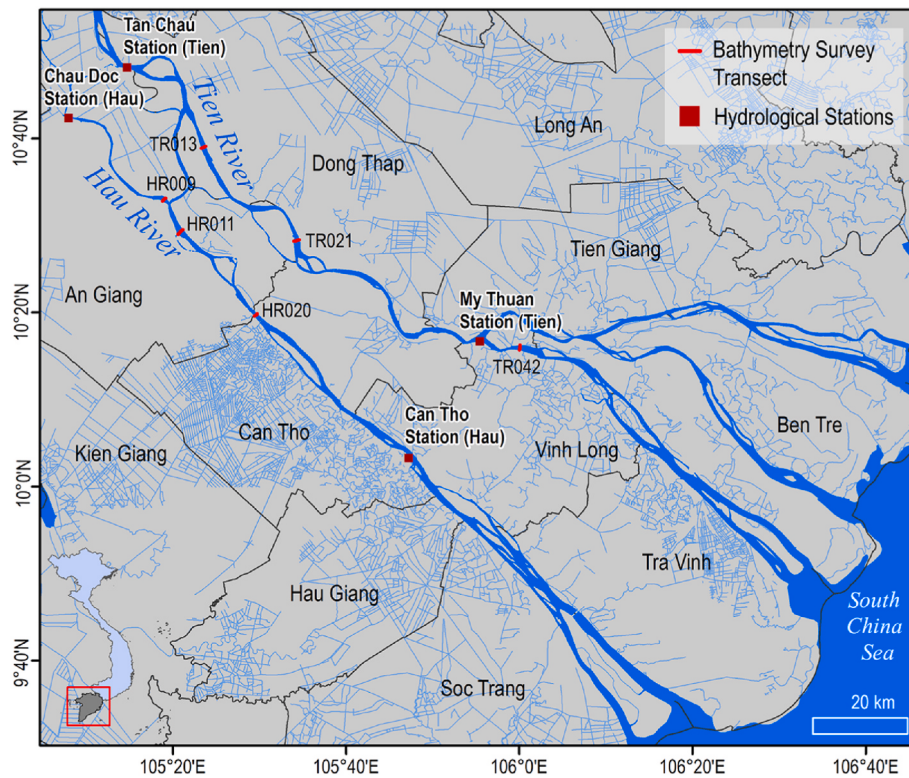


Fig. 1. The study area encompasses the Vietnamese Mekong Delta (VMD), covering the two main branches of the Mekong River flowing into Vietnam, Tien and Hau Rivers. Hydrological stations My Thuan and Can Tho mark the upstream and downstream sections of the Tien and Hau Rivers within the VMD, respectively. The governance of the VMD is decentralized, with sand extraction managed independently within the political borders of each province.

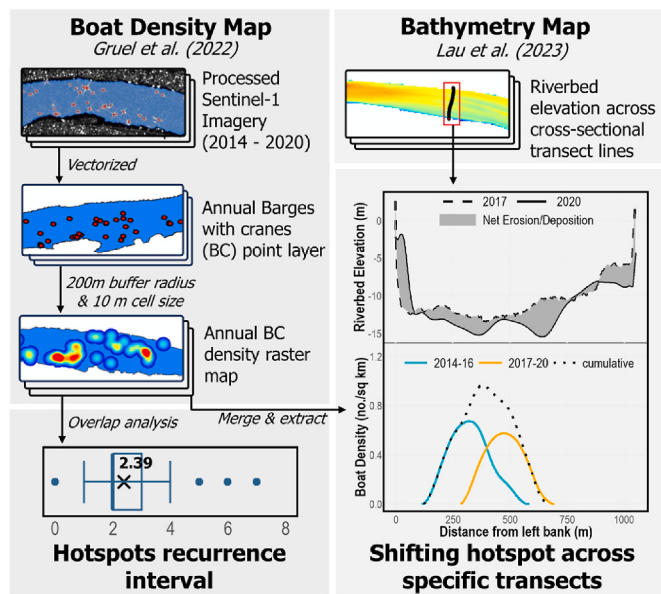


Fig. 2. Methodological flowchart for sand mining hotspot identification, and recurrence interval calculation based on Sentinel-1 satellite data, as described by Gruel et al. (2022). Boat density rasters were used to extract and correlate bathymetry and boat density values at specific cross-sections in the VMD, revealing the relationship between sand mining activities and their impact on the riverbed.

elevation angle. A threshold of >70 m was established as a reliable statistical representation of detected sand mining boats. This value was supported by fieldwork conducted in 2020 and 2021 (Gruel et al., 2022; Supplementary Text 3). Although complete coverage was only available

for 2015 and 2019, with approximately 55% coverage in the other years, low coverage sections were mostly in downstream areas that exhibited low sand mining activity. A boat density map with a 10-m cell size was generated to visualize the data. Yearly and cumulative BC locations were compared using the Overlap Analysis Tool developed by the Environmental Systems Research Institute for ArcGIS software. This tool facilitated “hotspot” identification and determination of recurrence frequency from 2014 to 2020. Recurrence intervals, ranging from 1 to 6 years, were calculated, distinguishing between continuously occurring hotspots and those that did not reappear. The largest overlap in each hotspot represented its recurrence interval. The recurrence intervals were illustrated through a histogram and a box-and-whisker chart, providing the average recurrence interval of sand mining hotspots in the VMD (Fig. 2).

2.3. Dynamic hotspots – correlating bathymetric changes in sand mining activities

In the second phase, we focus on examining sand mining boats’ direct influence on riverbed morphological changes using BC locations and density from phase one, and bathymetry surveys provided by Lau et al. (2023). In Lau et al. (2023), extensive field bathymetric surveys were carried out in the VMD from 2017 to 2022 to assess riverbed morphological changes. Using various echosounders, 196 survey transects spanning the Hau River, Co Chien and Cung Hau Branches, and upper Tien River were made in 2017, 212 tracks covering the entire VMD were made in 2020, and 65 survey transects encompassing the upper Hau and Vam Nao Rivers were carried out in 2022. Specifically, at 1 km segments of a section along the Tien and Hau River each, we compared the number of BC to the maximum incision recorded between 2017 and 2020. Additionally, to provide a more detailed and accurate reflection of the influence of boat density movement on localized river incisions, several representative survey transects were selected for

in-depth analysis. We also assessed the direct influence of sand mining on riverbed sedimentation by calculating net erosion and deposition volumes based on bathymetry differences between 2017 and 2020. To estimate these differences, we calculated the integral of the lines formed by the bathymetry, i.e. by calculating the area under each point across a simplified 1 m width of the transect. For each transect in each year, hence, the area under each point across the width of the transect (m^2) was multiplied by its elevation (m) before they were summed up to give the integral of the transect. The difference is calculated between the two years to attain the net erosion or deposition volumes, where a positive value indicates deposition while a negative value indicates erosion.

3. Results and discussion

3.1. Sand mining boat distribution across the delta

The Sentinel-1A satellite data, processed by Gruel et al. (2022), illustrates a cumulative density map of BCs in the VMD from 2014 to 2020 (Fig. 3a). Enlarged details of the map highlight several river stretches with high BC density (>4 BC per 200 m, depicted in red). Contrary to previous studies that reported more sand mining along the Hau River compared to the Tien River in 1998–2008 (Brunier et al., 2014), our study period showed the Tien River exhibiting more intensive and dynamic hotspots compared to the Hau River. Of the 1181 BCs identified in the VMD (2014–2020), 789 were in the Tien River and 344 in the Hau River, with around 70% concentrated upstream (i.e., of My Thuan and Can Tho stations). Hotspots along the Hau River are also notably concentrated upstream of Can Tho station (referenced in Fig. 1).

Our study also revealed a consistent growth of 32.4% in the number of BC from 2015 to 2020, following a sharp decline from 2014 to 2015 (Fig. 3b). In 2014, BC peaked at 215 boats, declining by 41.8% to 125 boats in 2015. This trend could have been influenced by the promulgation of Vietnam Prime Minister Directive No. 03/CT-TTg dated March 30, 2015 on "the enhancement of the effect of the legislation on minerals particularly on river sand mining", which assigned sand mining activities to be directly managed by principal authorities (Prime Minister, 2015). Subsequently, a gradual increase ensued, reaching 185 boats by 2020. Given BC's association with sand mining hotspots, the rising frequency of BC observations in the VMD signifies an intensification of sand mining

from 2015 to 2020. This trend aligns with the increasing sand mining budget (from 1.9 to 9.5 Mm^3 annually) calculated by Gruel et al. (2022) using bathymetry data. Notably, this intensification persists despite regulatory measures against illegal sand mining, as evidenced by the 2015 and 2017 amendments to Vietnam's Criminal Code (Hoi and Nguyen, 2021).

Spatial variabilities were found in the BC distribution between the two main rivers, and across the nine provinces – Dong Thap, Vinh Long, An Giang, Tra Vinh, Can Tho, Ben Tre, Tien Giang, Hau Giang, and Soc Trang. Across the different provinces, Tien Giang stands out for its official declaration to cease the issuance of sand mining licenses between 2013 and 2022, in their effort to mitigate the adverse effects of sand mining on riverbed and bank erosion (Thoa and Truong, 2022). However, our observations revealed that despite this measure, 52 out of 1181 (4.4%) BCs were still located in this province, consistent with findings from Jordan et al. (2019) and Yuen et al. (2024a). Yuen et al. (2024a) reported an extraction rate of 2.5 Mm^3/yr in Tien Giang province between 2018 and 2020, with 13 BCs observed during this period by Gruel et al. (2022). This inconsistency underscores the persistence of sand mining activities even in the province that has supposedly suspended licensing. Moreover, beyond Tien Giang province, BCs were also found within the management boundaries of other provinces that do not issue licenses (Kumar et al., 2023). This implies that the measures implemented by the authorities have been ineffective in preventing viable sand mining hotspots from being exploited (Yuen et al., 2024a), and necessitates a closer examination of the enforcement and regulatory mechanisms in place. The persistent activity is likely driven by factors beyond legislative limitations, such as financial considerations, profit margins, and the availability of extractable sand volume in the region driven by a high demand for infrastructure development and urbanization projects.

3.2. Recurrence patterns of sand mining hotspots

Of the 1181 BCs recorded from 2014 to 2020, 722 hotspots were eventually identified using the Overlap Analysis Tool (Fig. 3c). These hotspots were further categorized into 8 groups based on their recurrence intervals: 1-year, 2-year, 3-year, 4-year, 5-year, and 6-year intervals, as well as hotspots that were consistently active every year from

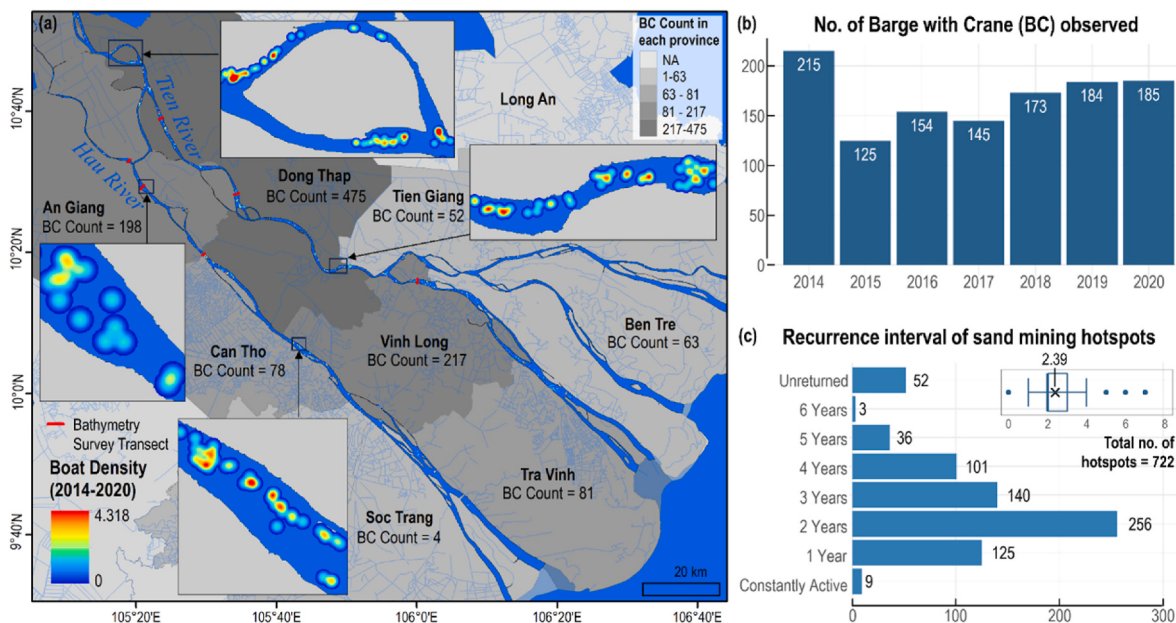


Fig. 3. Sand mining intensity and dynamics across the Vietnamese Mekong Delta (VMD) from 2014 to 2020. (a) Barge with crane (BC) density raster depicting sand mining locations and intensity with several hotspots shown in the enlarged figures. (b) Processed Sentinel-1 SAR data shows an increasing number of BC recorded across this period. (c) The recurrence interval of hotspots in the VMD, with median and modal recurrence intervals both averaging 2 years.

2014 to 2020, and those that did not reappear since their initial occurrence from 2014 to 2019. Spatial patterns were particularly evident along the Tien River. Constantly active hotspots were concentrated on the upper section of the Tien River (9 BCs), while unreturned hotspots (52 BCs) predominate in the downstream portion of the VMD, beyond the My Thuan and Can Tho hydrological stations (See Figs. 1 and 3a). This spatial distribution implies that the upper Tien River experiences sufficiently high deposition rates, allowing for consistent, yearly sand extraction over a span of at least 7 years from 2014 to 2020. In contrast, the prevalence of unreturned hotspots in the downstream VMD suggests a lack of sufficient sand volumes compounded by the low quality of the sand, which contains 30% mud (Gugliotta et al., 2017), making extraction unattractive due to small profit margins or potential environmental and economic losses. The lower sand deposition rate in this region also hints at a consequence of excessive sand mining upstream, exacerbating the scarcity of sand downstream (Rentier and Cammeraat, 2022).

Our findings also reveal that more than 50% of sand mining boats return to the same location after 1–3 years. Notably, 35.4% of these hotspots (256 out of 722) exhibited a 2-year recurrence interval, which is the most prevalent recurrence pattern. This could suggest that the annual volume of sand extraction in the VMD exceeds natural replenishment rate by at least double, underscoring the unsustainable nature of current sand extraction practices in the delta. Key factors that support this interpretation include the fundamental role of sand availability in determining sand mining boat mobility, the imbalance between sand supply and demand in the delta, and the unnaturally large changes in riverbed elevation that correlate with boat recurrence patterns.

Considering that the principal driving force of sand mining activities is the availability of sand (Leal Filho et al., 2021), dredgers are only likely to revisit a site when economically viable volumes of sand are present. This means that they are unlikely to move to a new location if there is adequate supply or substantial sand deposits at their existing sites, as indicated by the nine constantly active hotspots (Fig. 3). Conversely, if dredgers relocate, it strongly suggests that the previously mined sites are no longer economically viable, given the sand industry's economic underpinnings. These frequent shifts in sand dredging locations are, hence, clear evidence of depleted areas. Therefore, although we lack precise data on the sediment loads in the delta, the median 2-year recurrence interval can be broadly interpreted as the minimal period required for sufficient natural sand deposition to make a site economically viable again. This 'minimal' period is highlighted because it is likely that miners will continue exploiting active hotspots or resume operations before full recovery – a particularly probable scenario in the VMD where rising sand demand far exceeds supply in the delta.

In recent years, sediment supply into the delta has been severely depleted due to persistent dredging and sediment reduction from upstream dams (Binh et al., 2020b; Hackney et al., 2020). Specifically, the sand extraction rate in the VMD is estimated at 34.92–53.25 Mm³/year (Kumar et al., 2023), while sediment trapped by upstream dams ranges from 11.3 Mm³/year (Kondolf et al., 2014) to 96.8 Mm³/year (Binh et al., 2021). Concurrently, sand demand continues to rise, driven by rapid urbanization and infrastructure development (Bendixen et al., 2019), both domestically and from neighboring countries (Yuen et al., 2024b). This is reflected in most river reaches of the VMD, except in areas with imposed restrictions (Bravard et al., 2013). The significant imbalance between sand supply and demand has led to notable riverbed elevation reductions in recent years, as documented by Brunier et al. (2014) and Lau et al. (2023), highlighting that extraction has already outpaced replenishment in the region, resulting in chronic sediment deficits. This excess demand also implies that instances where dredgers do not return to a site immediately after it has fully recovered will be rare, though it assumes that sand dredgers continuously survey for potential or best sand excavation sites.

3.3. Shifting hotspots correlation with bathymetric changes

Beyond factors related to sand resource availability in the delta, the alignment of sand mining boat recurrence patterns with bed elevation changes from Lau et al. (2023) further supports our interpretation of the unsustainable nature of current sand extraction practices in the VMD. Three representative transects from the Tien and Hau Rivers were selected to elucidate the relationship between sand mining hotspots and riverbed incision (Fig. 4a and 5a). Cumulative boat density and bathymetry data from 2017 to 2020 were graphically plotted for comparison. The 2017 bathymetry data was paired with boat density information from 2014 to 2016, while the 2020 data was taken to reflect riverbed changes occurring between 2017 and 2020, coinciding with the period of boat density analysis. The selected transects seem to reveal a spatial-temporal association, with high sand mining boat density corresponding to large riverbed incisions. This correlation was particularly evident across TR013 along the Tien River (Fig. 4a), where erosional pits of 5 m deep were detected directly beneath sand mining hotspots. Such substantial incisions within a 3-year period are clearly unnatural morphology resulting from mining activities. Along the Hau River, across HR011, shifting patterns of sand mining boats also seem to align with erosional and depositional changes. Notably, as sand mining boats moved from the right to the left bank, erosion appeared to follow this shift on one side, while deposition was observed on the opposite side (Fig. 5a). While natural channel migration could contribute to these erosional patterns, the contribution of sand mining activities cannot be dismissed. Conversely, in transects TR042 (Fig. 4a) and HR020 (Fig. 5a), where there was a decrease in sand mining boat density across the study period, sediment depositions of up to 5 m were observed.

Additionally, a wider assessment along the longitudinal length of the rivers further reinforces the correlation between the dynamic relocation of sand mining hotspots and bathymetric changes. In the two sections of the Tien and Hau Rivers, segments with significant incisions corresponded with high numbers of sand mining boats. This was particularly evident along the Tien River section (Fig. 4b), where widespread sand mining boats coincided with deep incisions. In several highlighted sections (red circles, Fig. 4b), as much as 18 m of elevation change was recorded in segments with more than 10 sand mining boats within the same period. However, the absence of sand mining boats did not appear to be directly correlated with smaller incisions, especially in the Hau River section. There, large segments exhibited notable incisions despite the absence of sand mining boats (Fig. 5b). This discrepancy could be due to the temporal differences between the bathymetry and boat density datasets, or it might indicate that factors beyond sand mining activities contribute to these morphological changes. These additional factors are discussed in detail in section 3.4.

3.4. Contribution of sand mining to erosion and deposition changes

Between the upstream and downstream stretches of the rivers, we also notice a decrease in the volume of sand incised recorded at each transect downstream (Fig. 6b). This transition from net erosion to net deposition might be attributed to reduced sand extraction downstream, as indicated by our boat density analysis (Fig. 3), or possibly sediment contributions from bank collapses (Shu et al., 2019). The increased bank collapse recorded in the VMD (Hackney et al., 2020; Tuyen, 2022) could have led to significant sediment deposits in the downstream regions. For instance, at HR020 along the Hau River (Fig. 5a), several bank collapses have been documented upstream. These collapses could have contributed to sediment depositions calculated there, in addition to the lowered boat density. Tien River, overall, also experienced net erosion upstream but showed substantial sediment deposition downstream.

Furthermore, in the upstream regions where sand mining activities are predominant, changes in bathymetry might be influenced by factors beyond direct sand extraction along the transects. These factors include sediment losses from upstream dams (Binh et al., 2020b; Jordan et al.,

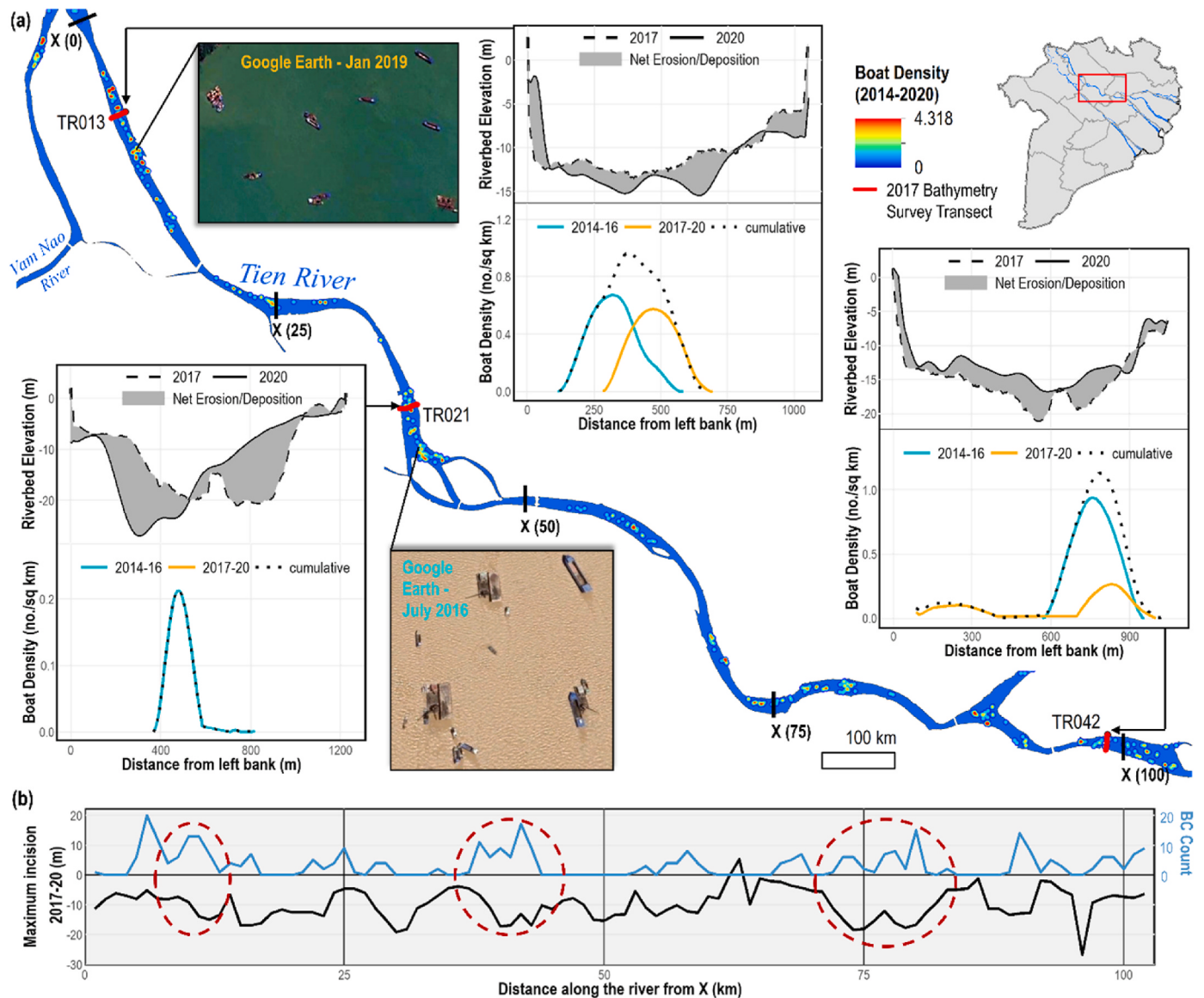


Fig. 4. Relationship between boat density and bathymetry along the Tien River. (a) Three selected cross-sectional transects highlighted to show the relationship between boat density and bathymetry, between 2014 to 2016 (blue) and 2017 to 2020 (yellow). The shaded area between the bathymetry of 2017 and 2020 represents the net volume of erosion or deposition at each transect during this period. Google Earth images provide a visual representation of sand mining boats identified from satellites. (b) Along the longitudinal profile at 1 km intervals from point X, significant riverbed incisions (black) generally corresponded to high numbers of Barges with Cranes (BC) recorded (blue). Notably, the red dashed circles highlight regions where a noticeable positive correlation between boat density and riverbed incisions was observed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2020), natural river flow (Nguyen et al., 2023) or sand mining sites located at a distance (Thi Kim et al., 2020). In an example at transect TR013, located upstream of the Tien River (Fig. 4a and 6a), there was a net sediment loss volume of 1660 m^3 between 2017 and 2020 (Fig. 6b). Despite a slight decline in boat density from 2014 to 2016, a large concentration of sand mining hotspots was observed both upstream and downstream, with relatively short recurrence intervals of 1–3 years (Fig. 6). Extractions in these areas could have resulted in sediment redistribution (Jordan et al., 2019) and consequently, slope changes and losses in areas not directly mined. Similarly, slightly downstream of TR013, transect TR021 also recorded 1556 m^3 of erosion between 2017 and 2020 (Fig. 6b) despite the absence of sand mining boats directly over the transect (Fig. 4a). It is also worth considering that the volume of sand extracted per sand mining site might have increased, contributing to sediment losses without a corresponding increase in sand mining boats. Nevertheless, our study underscores the intricate relationship between sand mining and riverbed dynamics, demonstrating that the

environmental repercussions of sand extraction extend beyond the immediate extraction sites. This highlights the need for a thorough spatial and temporal assessment of all contributing factors to effectively address sand mining issues in the delta.

4. Nurturing sustainability in riverbed sand mining: implications and strategies

By examining the patterns of sand mining boats and their association with the significant alterations in riverbed elevation, along with an understanding of sand resource availability in the delta, we conclude that the current rate of riverbed sand mining in the delta appears highly unsustainable. Achieving sediment equilibrium for the Tien and the Hau Rivers of the VMD would require urgent and effective management efforts (Eslami et al., 2019; Yuen et al., 2024a). Our study sheds light on two key elements that can be incorporated into future measures.

Firstly, our study provides valuable insights for policy improvement

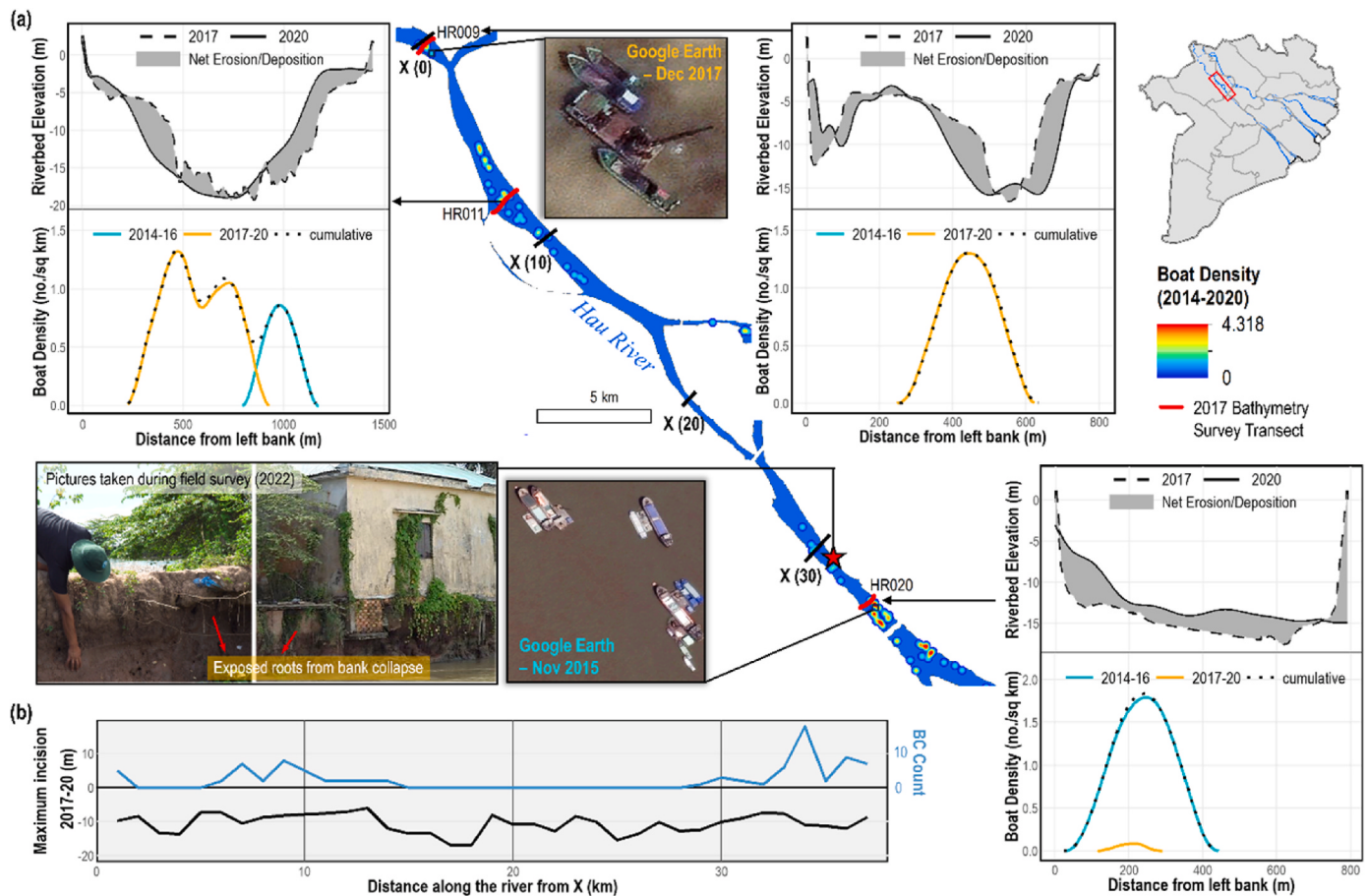


Fig. 5. Relationship between boat density and bathymetry along the Hau River. (a) Three selected cross-sectional transects highlighted to show the relationship between boat density and bathymetry, between 2014 to 2016 (blue) and 2017 to 2020 (yellow). The shaded area between the bathymetry of 2017 and 2020 represents the net volume of erosion or deposition at each transect during this period. Google Earth images provide a visual representation of sand mining boats identified from satellites, while bank collapse photos (represented by red stars) illustrate the potential contribution of sediments from bank erosion. (b) Across the longitudinal profile at 1 km intervals from point X, although riverbed incisions (black) generally corresponded with an increase in the number of Barges with Cranes (BC) recorded (blue), some segments without BC also exhibited significant incisions. This suggests the influence of factors beyond sand mining activities on riverbed changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in the VMD by offering recurrence interval information, which can be utilized to estimate the maximum timeframe for authorities to anticipate and intervene in sand extraction operations. The knowledge that the highest proportion (35.4%) of sand mining hotspots exhibit a 2-year recurrence interval, along with more than 50% of boats returning to the same hotspots within 1–3 years, enables the identification of areas at high risk of sediment depletion. This allows for prioritization of manpower, localized enforcement, and monitoring efforts. Sand mining management authorities can now allocate resources more effectively between areas with lower or higher extraction frequencies, ensuring a targeted and proactive approach to regulation. This is pivotal for the VMD, which currently faces significant management challenges (Schiappacasse et al., 2019) due to data transparency issues and limited enforcement. This has led to rampant and excessive rates of illegal mining activities (Yuen et al., 2024a) despite legislative efforts to control it (Lam, 2022). With the improved visualization of the dynamic nature of sand extraction activities in the VMD provided in this study, it is expected to aid in the development of more targeted and coordinated sustainable sand management practices (Dung, 2011). Moreover, a detailed understanding of sand mining boat movements would also enable researchers to more effectively explore its associations with various environmental aspects, particularly the ecological impacts of sand mining—a critical area that urgently requires further research (Park, 2024).

Secondly, the integrated use of remote sensing and bathymetry field

survey data to track sand mining activity in this study presents a promising avenue for provincial authorities to address both manpower and technological limitations. Remote sensing techniques, such as satellite Sentinel-1A data and Google Earth images, enable efficient detection of sand mining hotspots and provide a valuable tool for real-time monitoring (Gruel et al., 2022; Kumar et al., 2023). Adopted from Gruel et al. (2022), this method has significant potential to enhance the monitoring and enforcement capabilities of authorities, particularly in regions with decentralized license granting like the VMD. Furthermore, this method is scalable and can be applied to the entire Mekong River, as well as other large rivers in SEA where intensive and illegal sand mining is prevalent. This includes the Red River Delta in Vietnam (Runeckles et al., 2023), Irrawaddy in Myanmar (Gruel and Latrubesse, 2021), and Progo and Jeneberang in Indonesia (Ikhsan et al., 2021). As for the bathymetry surveys conducted by Lau et al. (2023), while carrying out annual surveys across the entire river network is resource-intensive and costly, focusing on representative river sections can facilitate calibration and validation of remote sensing methods and allow for detailed assessments at focused hotspots. Consequently, this integrated method can provide important insights into sand extraction and depositional rates in heavily mined rivers of the world. Additionally, to bolster monitoring efforts, it is imperative to actively involve local communities and civil society in this process. For example, establishing a VMD website hub to provide access to sand mining monitoring and licensing data and reports could be instrumental. This engagement not

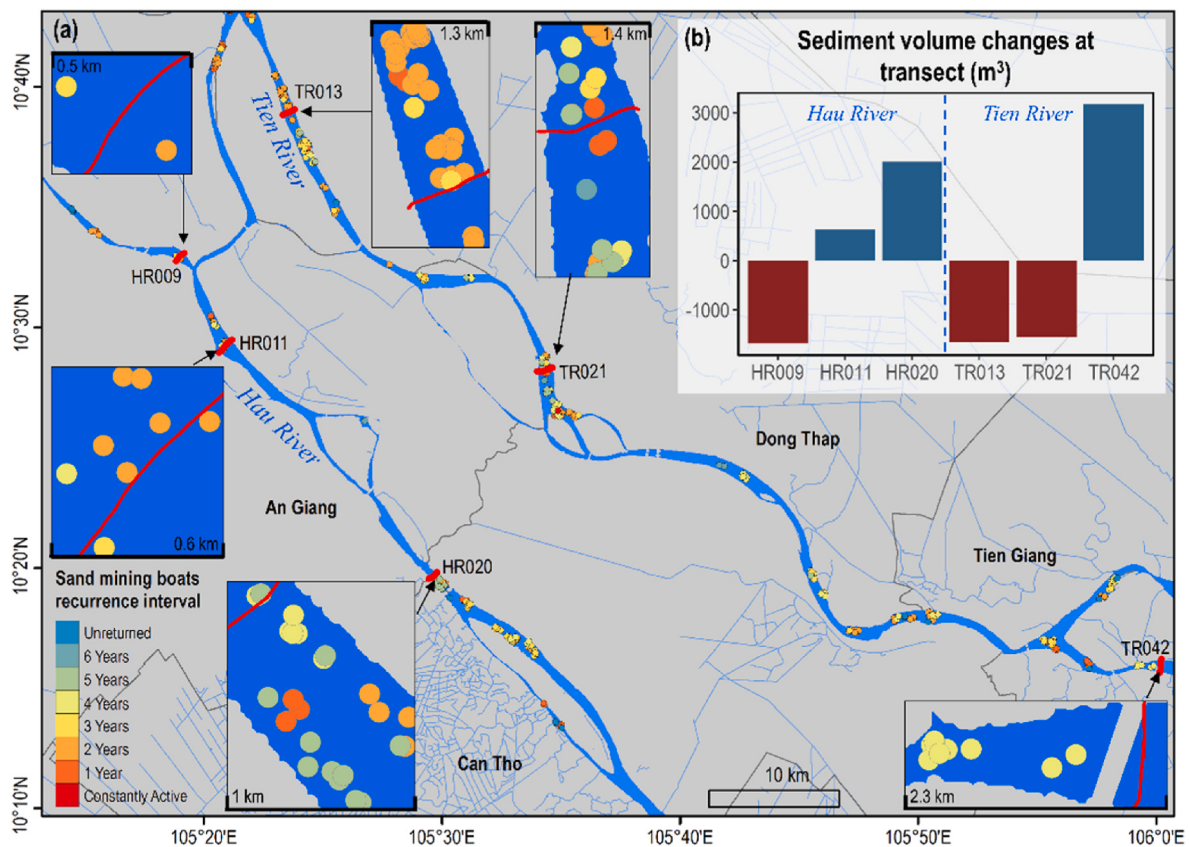


Fig. 6. (a) Sand mining boats' recurrence interval at six representative transects in the VMD from 2014 to 2020, considering a zone up to approximately 2.5 km. The most common recurrence interval is 2 years. Downstream reaches recorded larger recurrence intervals (4–5 years) than upper reaches. (b) Bar graph represents the net deposition (>0) and erosion (<0) volumes at the selected transects based on bathymetry difference between 2017 and 2020. The integral of each transect is calculated by multiplying the area under each point across the width of the transect (m^2) by its elevation (m) for each year, with the difference between the two years revealing the net erosion or deposition volumes. Downstream transects, such as TR042 and HR020, experienced the biggest deposition, while upstream transects experienced high erosion volumes.

only serves as an additional source of valuable data but also cultivates a sense of responsibility for environmental stewardship among community members (Gerlak et al., 2023).

5. Conclusion

This study investigates the dynamic shifts in sand mining hotspots and their association with bathymetric changes within the VMD from 2014 to 2020, utilizing a combination of Google Earth imagery, remote sensing, and bathymetry data. Analysis of Google Earth imagery and Sentinel-1A satellite data reveals a consistent 32.4% increase in sand mining hotspots from 2015 to 2020, with 70% of these hotspots concentrated in the upstream sections of the VMD. Significant sand mining activities were also identified in VMD provinces that lack official licenses, emphasizing the need for targeted management and enforcement efforts to combat excessive illegal sand mining that continues to threaten the entire delta's ecosystem. By examining the spatial and temporal variations of the sand mining barges, our study also unveils the highest proportion of boats with a 2-year recurrence interval. Considering factors such as sand resource availability and their role in determining sand mining boat mobility, as well as the association of sand mining boats and the riverbed elevation changes, this could imply an annual sand extraction rate of at least double the areas' natural replenishment rate. Although this interpretation of riverbed recovery based on boat analysis is conservative, highlighting the unsustainable nature of current sand extraction levels in the VMD remains valuable given the challenges in measuring recovery rates and the limited knowledge in this area.

Our findings significantly enhance the understanding of the temporal dynamics and recurrent patterns of sand mining hotspots in the VMD relative to local replenishment rates, providing nuanced insights into the sustainability and persistence of sand extraction activities (Hackney et al., 2021). At the same time, it also emphasizes the complex relationship between sand mining and riverbed dynamics by highlighting regions where other factors such as bank collapse, upstream dams, and bed slope changes may play a larger role in influencing erosional and depositional patterns compared to mining itself. However, to accurately assess the full extent of mining's impact and understand the roles of other contributing factors, as well as to achieve a more precise estimation of sediment replenishment rates, future studies should include detailed field surveys on sediment fluxes and sand stocks in the VMD. Only through these comprehensive assessments can we effectively manage sand resources in the delta and ensure long-term sustainability in the region.

CRediT authorship contribution statement

Rachel Yu San Lau: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Edward Park:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Yu Qing Koh:** Writing – original draft, Methodology, Data curation, Conceptualization. **Dung Duc Tran:** Writing – review & editing, Visualization, Data curation. **Sameh A. Kantoush:** Writing – review & editing, Validation. **Doan Van Binh:** Writing – review & editing, Methodology. **Ho Huu Loc:** Writing – review

& editing, Methodology.

Declaration of competing 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.

Data availability

Data will be made available on request.

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