New systemically measured sand mining budget for the Mekong Delta reveals rising trends and significant volume underestimations

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Abstract

The river beds of the Mekong Delta are some of the most intensively sand mined places in the world, however sand mining budgets are limited to rough and indirect estimates. Here, we provide a systematic, semi-physically based estimation of the Mekong Delta's sand mining budget. We provide a quantified budget that overcomes limitations resulting from previous reliance on officially declared statistics and bathymetric surveys of short channel reaches. We apply Sentinel-1 radar imagery to monitor the distribution of sand mining activities using boat metrics-driven mining intensity maps correlated with a field-based bathymetry difference map derived from two extensive bathymetric surveys of ~100 km reaches in the Tiền River conducted in 2014 and 2017 that cover ~15% of the Mekong Delta. We then extrapolate the Tiền River findings to the broader Vietnamese Mekong Delta from 2015 to 2020 and measure a continuous increase of the extraction budget by ~25% between 2015 (38 Mm^3/yr) and 2020 (47 Mm^3/yr). We estimate a total sand mining budget of 254 Mm^3 during the 6-year study period with an average annual rate of ~42 $Mm^{3.}$ Our semi-physically based annual rate differs from both official declarations provided and estimates from previous studies implying that a substantial portion of sand mining budget remains unaccounted for. Riverbed sand mining remains key threat to the Mekong Delta as it exacerbates or contributes to a multitude of other threats including dam construction effects on sedimentation, ongoing subsidence, sea level rise and recurring salt intrusion. This integrated study offers a new method that is readily implementable elsewhere to allow for extensive monitoring and quantification of sand mining activities that are vital for assessing future projections on environmental impacts.

Highlights

- A first semi-physically based estimation of sand mining budget in VMD is provided.
- Sand mining has increased by 25% for the whole VMD between 2015 and 2020 from 38 to 47 Mm^3/yr.
- Official declaration-based previous studies significantly underestimated the sand mining budget.
- Our methodology can be applied elsewhere independently from official declarations.

Keywords

Sand mining; Riverbed incision; Remote sensing; Mekong Delta; Sustainability.

1. Introduction

Rising sand demand for construction and land reclamation fueled by rapid population and economic growth in Asia has resulted in sand mining of major river beds at unprecedented rates[1–5] over recent decades. The process of riverbed sand extraction is commonly unregulated and the quantities and impacts remain largely hidden as the operations are submerged. River sand is not an infinite resource and it must be managed as the constant mining of riverbeds is responsible for multiple, knock-on, adverse alterations of river hydrology that can trigger irreversible transformations of natural and social-ecological systems that compromise livelihoods and cause significant deterioration to local ecosystem services[6–9].

Short term sand mining impacts include bank erosion, bed incision, and groundwater table modifications while in the longer term, sand mining compromises delta-wide water supply resources; intensifies saline water intrusion, and reduces floodplain connectivity[3,6,10–12]. Despite the well-known consequences, the study of sand mining is limited by a lack of regional data on extraction budgets that is primarily driven by a desperate absence of effective monitoring systems[13].

Illegal or unregulated sand mining is a global problem[14] and a general lack of a regulatory framework and licensing along with the inefficient monitoring means it is worryingly prevalent in Asia, particularly in Vietnam, Cambodia, and Laos[14–17]. The Vietnamese Mekong River has been heavily impacted by large-scale riverbed dredging since large scale operations started in the 1990s[16]. In the Mekong sand mining is primarily carried out by mechanical shovels on barges that feed a fleet of boats and barges. Operations tend to stay within the same concession area while actively dredging until an area is exhausted or the extraction license expires.

In Vietnam the number of mining licenses issued has increased sharply since 2005 as licensing was decentralized, changing from the national to provincial level. The decentralization severely inhibits the ability to determine the exact number and operational capacity of businesses in operation. This is likely due to inherent limitations on human resource and technical capacity in provincial governments, and limited coordination among the relevant departments[18]. The Vietnamese government predicted demand for sand from riverbed of around 2.1 to 2.3 billion m^3 between 2016 and 2020 and current projections stand at 1.5 billion m^3 by 2040 in the VMD[14,19,20]. However, accurate estimates on sand extraction in the VMD remain unknown, and scientific literature suggests that the volume of sand mined is likely to differ significantly from official statistics[21].

Assessing the environmental impacts caused by riverbed sand mining activities is complicated by the immense scale, the dynamic environment and limited regulatory power in the effected countries. There is an urgent need to examine novel approaches to regional based assessments of riverbed sand mining.

The multiple negative implications of illegal or unregulated sand mining activities in Southeast Asia have started to enter the environmental discourses and in the Vietnamese Mekong Delta (VMD) area, notable attempts in quantifying the mining budgets include, Bravard et al.[16] who surveyed extractors, provided an overview of the riverbed mining intensities along the Mekong and Brunier et al.[22] who analyzed a VMD bathymetry dataset between 1998-2008 highlighting the impacts of the excessive sand extraction. Beyond surveys, Anthony et al.[23] linked the shoreline erosion of the delta to riverine sand extraction, and Eslami et al.[20] analyzed the amplified salt intrusion partially driven by the intensive riverbed mining are also of noteworthy contributions.

With regard to budgeting approaches, Jordan et al.[21] measured the sand extracted volume along a short reach (20 km) of the Tiền River and provided a detailed extraction budgets in different provinces of VMD, regardless, mostly based on the declaration. In Cambodia, Hackney et al.[24,25] have focused their work on the bank instability related to sand mining and measured an inferred sand budget using PlanetScope imagery. To date attempts to estimate sand extraction values are either mainly locally estimated[21], thus only reflective of particular periods[22], or based on incomplete or inaccurate official declarations[16,20]. Estimations are inherently complicated by highly dynamic nature of the sector as barges can move on a daily-basis, and natural fluvial processes can gradually erase any trace of sand mining through deposition or reworking.

Here we provide the first estimation of the sand mining budget over the whole VMD (~700 km^2 of channel network) using a novel semi-physical measurement that overcomes the uncertainties and biases of existing approaches and published values. We first built a sand mining barge metrics using high-resolution imagery (Google Earth and PlanetScope), where we identified specific boat types to build a boat classification system. The metric was validated via a field survey during 2020-2021. The second step involved the development of a quantitative relationship between the boat intensity map driven by the time-series Sentinel-1 radar imagery and a bathymetry difference map (during 2014-2017) along an intensively mined 100 km reach in the Tiền River (covering ~15% of VMD). In final step the mathematical relationship was applied to the entire ~700 km^2 of the VMD to construct an annual sand mining budget and calculate incision rates between 2015 to 2020. Our new budgets were then compared geographically and historically with the previous estimations from different publications.

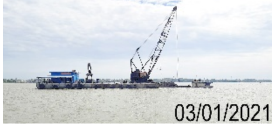
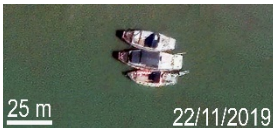
2. Results and Discussion

2.1. Sand mining boat activity and hotspots

Barges with cranes (BC) that are used for sand extraction comprises 10% of all boats associated with sand mining (Table 1, Supplementary Fig. 3). Barges used exclusively for sand transport (BT) are driven by pushers or pullers and represent 7%. The blue boats (BB) which make up 40% of all vessels are motorized and can also be used for other material or rice transport. The remaining 43% primarily consist of pusher-puller, ferry, fishing and passenger boats. Hotspots of sand mining are characterized by high concentrations of boats. About 82% of boats along our study reach were solitary, whilst 18% were connected to one or more boats. Focusing on the BC, 76% of them were connected to another boat (BT or BB) for sand filing. In contrast, only 25% of the BB were connected to a boat, for 59% of them were connected to a BC. Similarly, BT were mostly single or in 25% of the situation connected with a BC.

From Google Earth observations, single boat sizes displayed a normal distribution for all BC, BT and BB (Supplementary Fig. 3). While it is impossible to distinguish between BB and BT using length, the BC which is the core of the sand extraction activity is distinctive. However, single BC only occur in 24% of the total activity, because they are mostly connected to the other boats that carry sand. From analysis on Sentinel-1 radar, the size of the clusters composed of BC are then confounded with the clusters of BB. However, except when parked, most of the BB clusters that were surrounding the BC were used for sand mining purposes. Comparisons between BC observed on the field and their detection size on the Sentinel-1 of the same day have shown that 73% of the BC have a length above 70 m with most between 70 and 90 m in length.

Table 1 Boat typology along the section surveyed with Google Earth images correspondence (equal scale). Median and standard deviation of length and area.

Boat type	Google Earth image	Ground observation	Length (m)	Area (m^2)	Frequency (%)
Barges with Crane (BC)			M=37 STD=6	M=450 STD=97	10
Barges for Transport (BT)			M=47 STD=2	M=558 STD=52	7
Blue Boats (BB)			M=47 STD=7	M=376 STD=87	40
Other Boat and Pusher / Puller (OB / PP)			M=27 STD=13	M=168 STD=168	43

For the years 2014, 2016, 2017, 2018 and 2020, Google Earth images covered about 55% of the VMD. In 2015 and 2019 the VMD was fully covered by Google Earth. Of the area not covered, ~75% is located in the downstream part where sand mining activity is relatively low. BC activity in the VMD, was particularly high in 2014 with about 215 boats. It dropped by 42% to 125 in 2015 before increasing slowly again to 185 in 2020 (Fig. 1). The number of BC declined observed between 2014 and 2015 were mostly located in the Mỹ Tho, Hàm Luông and Cổ Chiên branches. In this part of the VMD, the number of BC dropped (R=0.40) between 2015 and 2020 while the upstream part of the Tiền R. increased (R=0.77) from 69 to 100. The number of BC in Hậu R. varied, albeit slightly, with little decrease and increase after 2016. The total number of BC located in channel were about the same in 2015 and 2016, but this difference increased from 12 to 22 between 2017 and 2020. A total of 7% of the BC within the VMD observed between 2014 and 2020 were not located in channel (study area), but along the bankside; this implies that they might have been parked or potentially used at night instead.

75% of the 244 BC located along the Tiền Section (TS) between 2014 and 2017 were located within an incised area (median of 200 m radius area). 93% of the BC with a surrounding boat density ≥3 boats/km^2 were also located within an incised area (R^2=0.13, slope=-0.76). The median of bathymetry difference values that were extracted from each pixel showed a continuous increase of the incision with in parallel of the boat density increase. Measuring the distance between the BC and all boats detected (N=42,054) on the VMD, 50% of the boats had a density above 1.7 boat/km^2 (Fig. 1). About 50% of the boats were located less than 224 m away from of a BC, and 50% of these boats had a density higher than 2.8 /km^2. The area covered by the 224 m radius of the BC buffer representing only 11% of the whole VMD area.

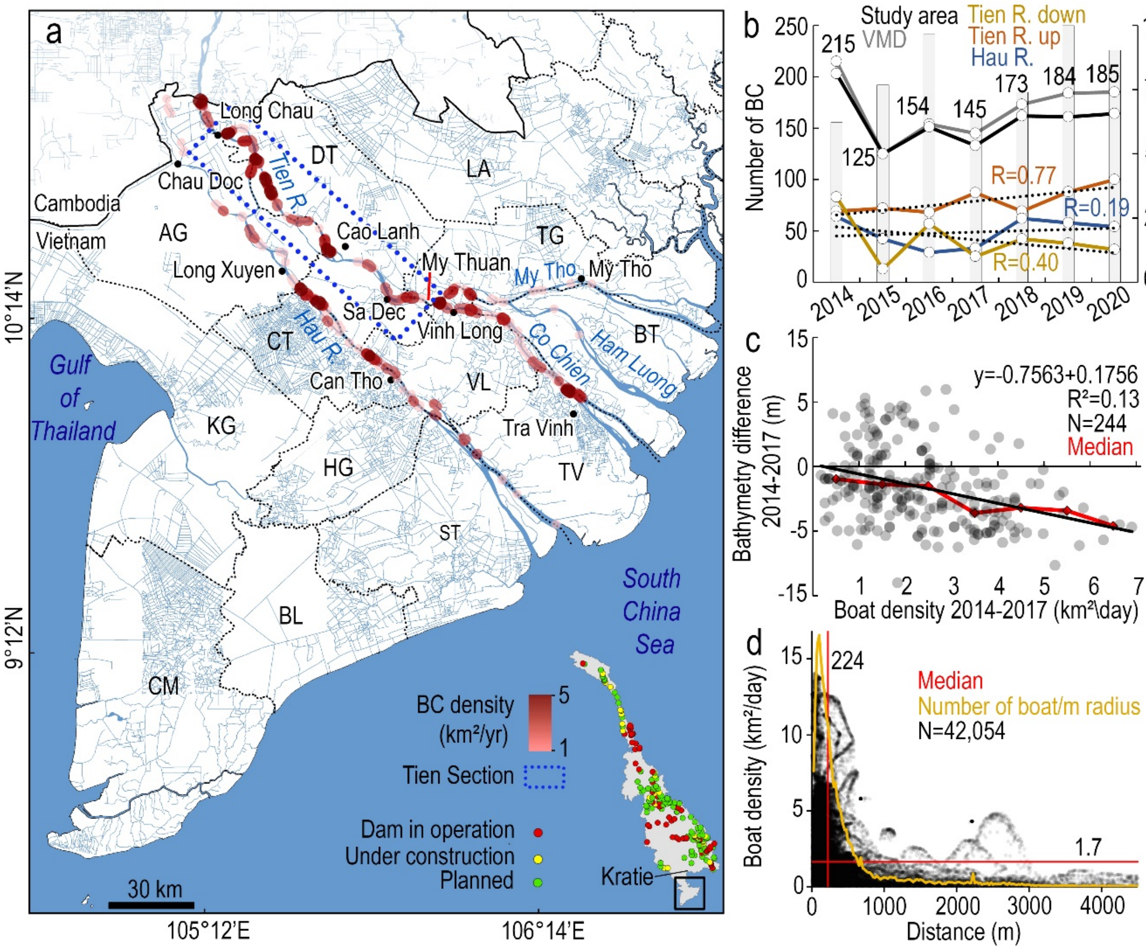


Fig. 1 Barges with crane number, distribution and distance with boats detected with Sentinel-1 between 2014 and 2020. a: Map showing the BC distribution (red stretch) between 2014-2020 and the intensity of the BC /1 km radius/year. The TS is delineated within the blue dotted rectangle. Black dots

correspond to the main riparian cities. Upper and lower Tiền R. are separated at the Mỹ Thuận arow. The inset map corresponds to the Mekong basin showing dams (Mekong River Commission). **b**: Evolution of the BC number over the period 2014-2020 in the VMD and in-channel study area, Tiền River: upstream and downstream, Hậu River. Histograms represent the proportion of Google Earth cover over the VMD per corresponding year and the black box to the VMD location. **c**: Median boat density (x) and the median of bathymetric difference surrounding the 200 m radius of each BC in the TS. **d**: Graph showing in x the distance between all boat (≥70 m) with the nearest BC (distance max 4,500 m). In y the density of boat surrounding each of these boats. The orange curve corresponds to the BC-Boat distance (m) frequency. The two red lines correspond to the x and y median. The wave shape between 1,000 and 3,000 m correspond mostly to part of channel where BC might have been present, but Google Earth images were missing.

Our sand mining boat density map over the VMD (Fig 1) shows large spatial variability. We identify several major sand mining hotspots along the Cambodian border on the Tiền River (Fig. 3 and Supplementary Fig. 4 and 5). Intensive extraction sites are also found to be located around the Long Khánh Island and the channel heading toward the Vam Nao as well as the Thuận Đông Island and around of Sa Đéc (Figs 2 and 3). Downstream of Mỹ Thuận, the major hotspot was around the Mỹ Tho and Cổ Chiên confluence, near Vĩnh Long city and around An Phước. The most downstream hotspot detected were downstream of the Co Chien bridge. On the Hậu River, the concentration appeared to be lower with the hotspots located near Cần Thơ, Bình Hòa, and Cái Dầu. Sand mining was also found to occur near Định An, a few km from the coast; this was confirmed by the observation of BC from Google Earth. In 2015, 59 hotspots have been detected in the VMD with an average of 0.29 km^2. In 2020, there were about 70 of such areas with a higher average of 0.34 km^2. Between 2015 and 2020 about 69% of the hotspots were located on the Tiền River, with an average hotspot area of about 0.44 km^2. Hotspots located downstream of Mỹ Thuận and Hậu River respectively represent 11% and 20% of the hotspots, with a smaller average area of 0.08 km^2.

2.2. Riverbed sand mining budget of the Mekong Delta

The bathymetry difference between 2014 and 2017 on the TS showed an average incision depth of 1.02 m (STD=2.6 m). Along the surveyed reach, 60% of the area experienced erosion, while 27% had deposition, and the remaining area experienced limited change between 0.5 and -0.5 m (Fig. 2). Median boat densities of the surveyed reach were about 0.35 boat/km^2 with 6% of this area showing more than 3 boats detected /km^2. 73.4% of the surveyed reach had boat densities of less than 1 boat/km^2.

By plotting incision rate against the boat density for every pixel, we obtain a R^2=0.88 of the median bathymetry difference (y=-0.7143x+0.0179) that corresponds to a median bathymetry difference about -1 m for areas with boat densities between 0-3. Beyond the threshold of 3 boats/km^2, the median difference in bathymetry decreased by 1 m (i.e., increased 1 m incision) per additional boat/km^2. By comparing the period 2014-2017 with 2018-2020 in the survey area we observe an increase boat density of ~ 32% of the average (from 0.85 to 1.13 /km^2). However, 47% of the places which experienced a density of more than 3 boats in 2014-2017 had reduced densities of boats (<2 boats/km^2) during the period of 2018-2020. This reduction in boat density is likely due to the depletion of the sand in these places or license expiration.

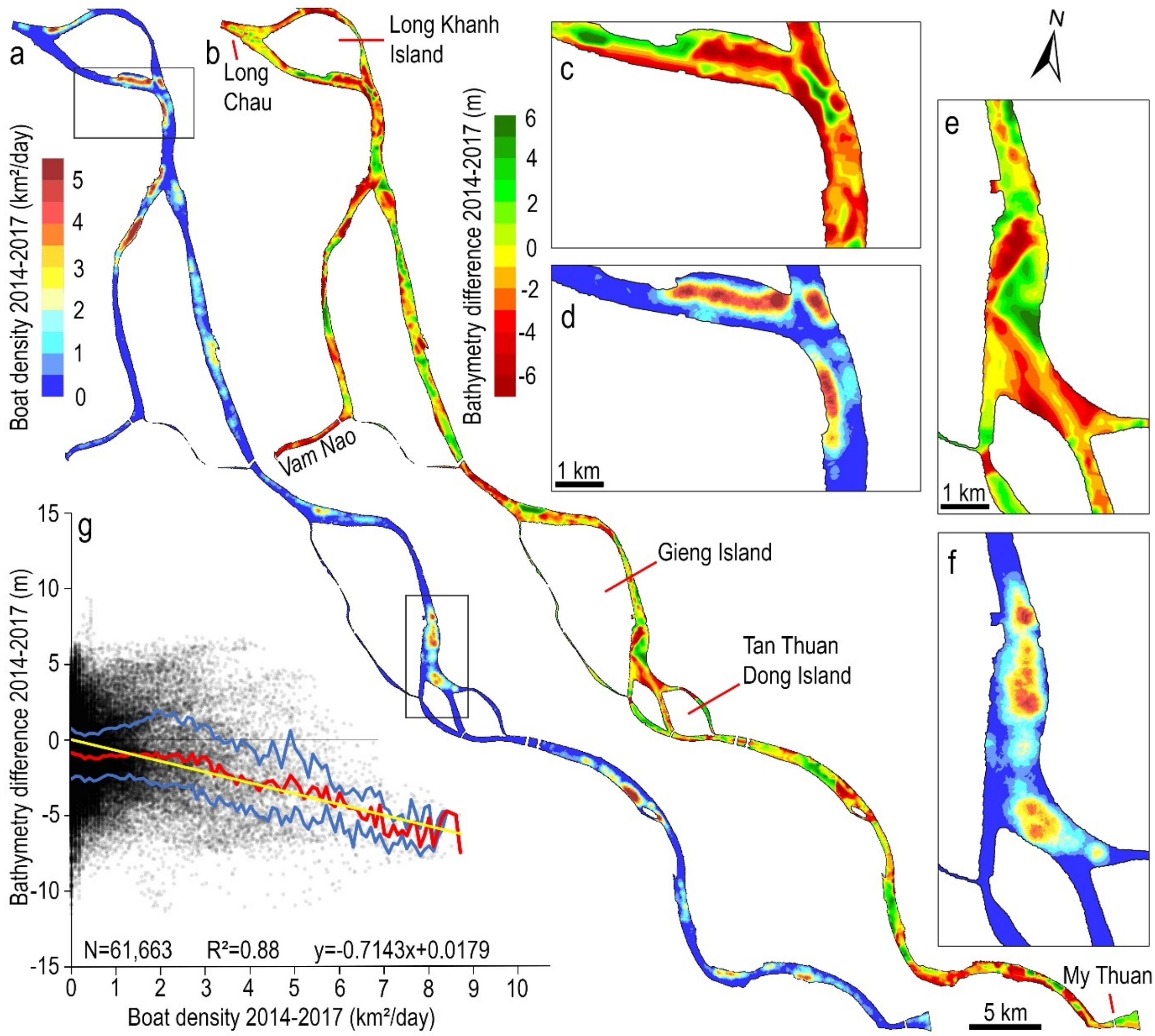


Fig. 2 Bathymetry difference and boat density along the TS. a, **d**, **f**: Boat density/km^2 2014-2017. **b**, **c**, **e**: Bathymetry difference 2014-2017. **g**: Boat density 2014-2017 versus Bathymetry difference 2014-2017 plotting at resolution 40 m. Blue lines correspond to Q1 and Q3, red line is the median of the bathymetry difference at each 0.1 boat density beam.

We calculate that a total amount of 253.58 Mm^3 of sand was extracted in the VMD during the period 2015 to 2020, with an average of 42.26 Mm^3/yr (Fig. 3, Supplementary Table 2 to 5). The most intensively mined reach lies upstream of Mỹ Thuận on the Tiền River and has a total extraction volume of 167.17 Mm^3 that represents ~66% of the total extracted volume in VMD. Hotspots downstream of Mỹ Thuận, had lower budget of extraction at 42.19 Mm^3 (~17% of the total). In contrast to the Tiền the Hậu River had a lower extraction budget of 44.22 Mm^3 (~17%).

The extraction volume continuously increased annually on the VMD with an average annual increase of 1.9 Mm^3 resulting in a 25% total increase in extraction volume (9.5 Mm^3) between 2015 and 2020. Notably, 2017-2018 experienced an increase of more than twice the previous years (3.17 Mm^3) while 2015-2016 and 2016-2017 experienced a milder increase of 1.30 and 1.38 Mm^3, the period. The period 2018-2019 and 2019-2020 showed increases of 1.62 Mm^3 and 2.03 Mm^3, respectively (Supplementary Fig. 4 and 5). This increasing trend is primarily due to extraction in the area upper Tiền River, which was observed to have a constant increase (34% between 2015-2020) in the volume of sand extracted. Sand extractions increase peaked in 2017 to 2018 with 2.71 Mm^3 (inter-annual difference in mean 1.62 Mm^3).

In the area downstream of Mỹ Thuận (inter-annual difference in mean 0.16 Mm^3) experienced only a mild increase in sand mining activity, and a decrease after 2019. The Hậu River also showed only a moderate initial decrease between 2015 and 2017 and a gradual but mild increase during the following years (inter-annual difference in mean 0.11 Mm^3).

Scaling up the entire VMD we imply that experienced a total incision about 0.34 m in 6 years with a rate of 0.06 m/yr. Among the three sections studied (Hậu River, Upper Tiền and Lower Tiền), the Lower Tiền experienced the least incision with a lowering about 0.09 m in 6 years corresponding to an average rate of 0.02 m/yr. In contrast, the upper Tiền R. reach up to the Cambodian border has experienced the deepest incisions of approximately 1.48 m in 6 years with an annual average rate of 0.25 m. In the Hậu R. we infer incision of by 0.16 m over 6 years, i.e., 0.03 m/yr.

The incision rates in the VMD were estimated to be around 0.13 m/yr by Brunier et al.[22] over a period 1998-2008. This value is more than 2 times higher than the average incision rate we calculated (0.06 m/yr) for the period between 2015 to 2020. More recently, Binh et al.[26] calculated an average incision rate of about 0.16 m/yr on the upper Tiền and Hậu Rivers over the period 1998-2014 and 0.5 m/yr for the period 2014-2017. We obtained an incision of 0.67 m/yr for the period 2015-2017 i.e., 0.22 m/yr in this part of the Tiền River and up to the border.

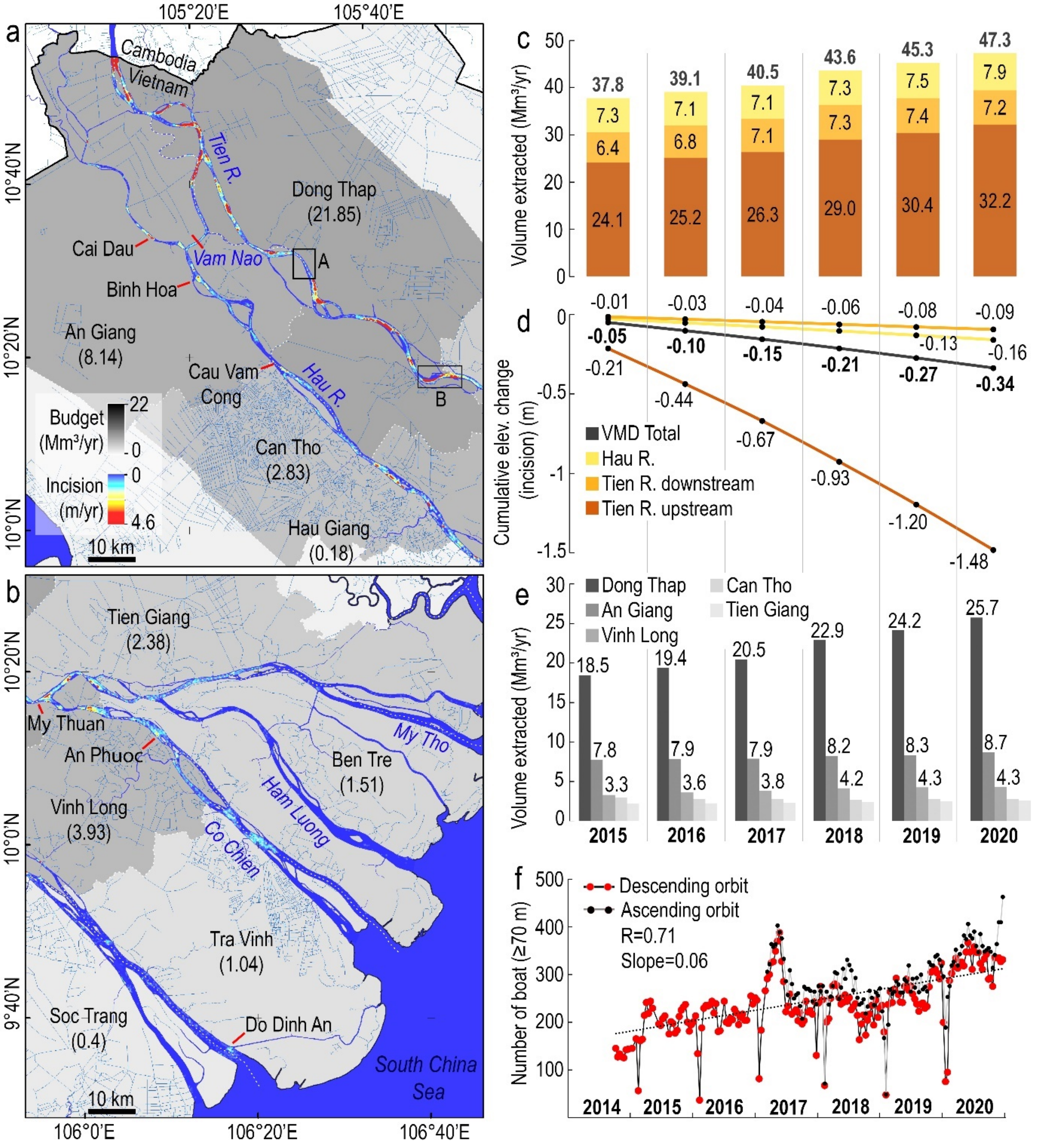


Fig. 3 Volume extracted, incision rates and boat activity. a and **b**: Map showing the sand mining hotspots and the average incision on the VMD. The province scattering from HDX and the average sand mining budget per province displayed in grey colors intensity. The 3 studied sections of the VMD (Upper and lower Tiền R., Hậu River) separations are indicated with the

red line at Vàm Nao and Mỹ Thuận. Sections A and B, which are discussed in Fig. 4, are demarcated by the black boxes. **c**: Volume extracted per year for the Tiền River upstream (brown), Mỹ Tho, Hàm Luông and Cổ Chiên branches (orange), the Hậu R. (yellow) and the VMD total (dark grey). **d**: Cumulative incision over the same period and sections with same colors as C. **e**: Top 5 provinces with the highest annual sand extraction budget (average ≥2 Mm^3/yr), corresponding to 93% of the budget (Supplementary Text 5, Table 7). **f**: Number of boats detected (≥70 m) per image between Oct 2014 and Dec 2020 for both ascending and descending orbit in VMD, the low values ~70 boats, observed annually correspond to the Lunar New Year period (~ February).

From 2015 to 2020, the average density boat of ≥70 m in length had increased by 68% from 0.21 boat/km^2 to 0.35 boat/km^2. The Upper Tiền R. had the most significant increase in large boats at 113% from 0.72 to 1.54 boat/km^2. In contrast, the lower Tiền R. shows a mild increase of large boat density of about 21% with only 5% on the Hậu River. Upon removing the anomalous data during the Lunar New Year period, the number of boats detected across the VMD has increased constantly (R=0.71 and slope=0.06) with an average of 202 in 2015, to about 325 in 2020 (61% increase). In the section A, we observed a stable activity between 2014 and 2020 with different boat intensities morning and evening, with an average about 0.2 boat/km^2 at 5.45 AM (morning) and an average density of 0.5 boat/km^2 at 6.10 PM (evening) (Fig. 3 and 4). In the section B, however, the difference was less significant: approximately 0.1 boat/km^2 difference between morning and evening orbits.

2.3. Budget and incision comparative analysis

Published sand mining budgets for the VMD, are primarily focused on either specific geographical areas of the delta[21] or relied on the official statistics[20,21]. A major regional sand mining budget of the VMD was estimated by Bravard et al.[16] who suggested a budget of 7.75 Mm^3 for the year 2012 based on declarations from extractors along part of the VMD (Table 2). Bravard[16] calculation equates to approximately ~8.5 Mm^3 in total if we extrapolate their value to our entire study area. Later, Brunier et al.[22], based their work on the bathymetry difference between 1998 and 2008 along part of the Hậu and Tiền Rivers claimed an average of 20 Mm^3/yr, i.e., 35.5 Mm^3/yr when extrapolated to the whole VMD. More recently, Eslami et al.[20] and Jordan et al.[21] estimated the budgets of 28 Mm^3 (2015) and 17.77 Mm^3 (2018), from the licenses issued and governmental institutions. These last two references referring to two different years obtain 28 Mm^3/yr and 22 Mm^3/yr extrapolated at the VMD scale (Table 2). We calculate an extraction volume of 37.8 Mm^3 for 2015. This is 35% more than the value provided by Eslami et al.[20]. Even more significantly, our estimation of 43.6 Mm^3 in 2018 is 2.5 times higher than the values of Jordan et al.[21]. For the period 1998-2008, Brunier et al.[22] reported more sand mining on the Hậu River (55%) than on the Tiền River. However, our calculation remarks only 17% of the VMD extraction from the Hậu River corresponding for 20% of the hotspots between 2015 and 2020.

Table 2 A comparative selection of reported sand mining budgets on the VMD.

Budget measured (Mm^3)	**Period (Years)**	**Studied covered reach (km^2)**	**Volume (Mm^3/ km^2/yr)**	**Annual budget Extrapolated at the VMD scale (710 km^2)**	**Data sources and methods**	**References**
7.75	**1** (2012)	**613** VMD Main stem of Hậu and Tiền	0.012	8.5	Field survey based on individual questionary for each extraction site. Location, granulometry, staff capacity, number of vehicle and equipment, number of years in operation, seasonal calendar, quantity extracted.	Bravard et al. (2013)
200 (90 Tiền – 110 Hậu)	**10** (1998-2008)	**400** 205 km on the Tiền 143 km on the Hậu	0.05	35.5	Bed volume change loss measured with bathymetry data from MRC	Brunier et al. (2014)
28	**1** (2015)	**710** VMD	0.0394	28	Issued mining licenses	Eslami et al. (2019)
17.77	**1** (2018)	**572** VMD Without Bến Tre and Tiền Giang provinces	0.031	22	Data collected from Institutions: Departments of Natural Resources and Environment (DONREs), the Southern Mineral Control Department (SMCD), Ministry of Natural Resources and Environment (MONRE)	Jordan et al. (2019)
4.64 (+/- 0.31) Mm^3	**1** (2018)	N/A Tiền R.	N/A	N/A	Bathymetric survey in April-May 2018 along 20 km of reach with MBES	Jordan et al. (2019)
2100 – **2300**	**4** (2016-2020)	N/A Whole Vietnam	N/A	N/A	Governmental declarations projections	Koehnken and Rintoul (2018)

253.58	**6** (2015-2020)	**710** VMD without bridge, ferry, houseboats, buffer –50 m	0.059	42.26	Bathymetry survey in 2014 and 2017 Field Survey in 2020 and 2021 Remote sensing using Sentinel-1 in 2014-2020	This study

According to Jordan et al.[21], the sand mining extraction in Tiền Giang Province in 2018 was found to be 0.51 Mm^3 despite being illegal. Similarly, whilst sand mining was prohibited in Bến Tre province, these authors could not verify if sand mining activity was truly absent. In comparison with Jordan et al.[21] our analysis on these provinces showed minor but constant extractions during the same period with the respective averages of 2.38 Mm^3/yr and 1.51 Mm^3/yr in Tiền Giang and Bến Tre (Supplementary Table 7). It should also be noted that Jordan et al. (2019) noted that their estimated rate in 2018 of Tiền Giang was likely to be under-estimated, which is substantially in-line the re-estimated value in this study of 2.42 Mm^3/yr. Similarly, while we estimated the rate of 1.51 Mm^3/yr in Bến Tre (1.57 Mm^3 in 2018), several BCs were clearly visible on the respective Google Earth image.

Between April and May of 2018, Jordan et al.[21] estimated an extracted volume of 3.59 Mm^3 along a 10 km reach (km 6 to 15 in Jordan et al.[21]), near Sa Đéc. Chronological observations of BC from Google Earth also detected by Sentinel-1 regarding the number of boats show that sand mining along this section might have started after 2015 (Fig. 4a). The activity becomes more prevalent and visible after September 2016 with an increase by 4 times until 2020. This implies that the area had already been intensively excavated for 1.5 years prior to the survey by Jordan et al.[21]. The numbers of BCs detected on this area between 2015 and 2020 have never exceeded eight until 2018 and were around 14 in 2019 and 2020. From 2014 to 2020, the numbers increased significantly to a total of 60 observed, accounting for 5.8% of all BCs observed across the VMD. Total sand mining measured on the section B for the same period was 18.87 Mm^3 corresponding to about 7.4% of the whole VMD budget for the period of 2015 and 2020. Between these 5 years, the volume of sand mined increased by more than two times. In 2018 the volume extracted was about 3.56 Mm^3 based on our boat density-based estimation. In the same year, field measurements by Jordan et al.[21] showed that 3.59 Mm^3 of sand was extracted in 8 pits that were ≥2500 m^2. Along this section we measured a total incision of 2.44 m over 6 years for an average year of 0.4 m/yr. In 2018 the incision due to sand mining was found to be at 0.46 m.

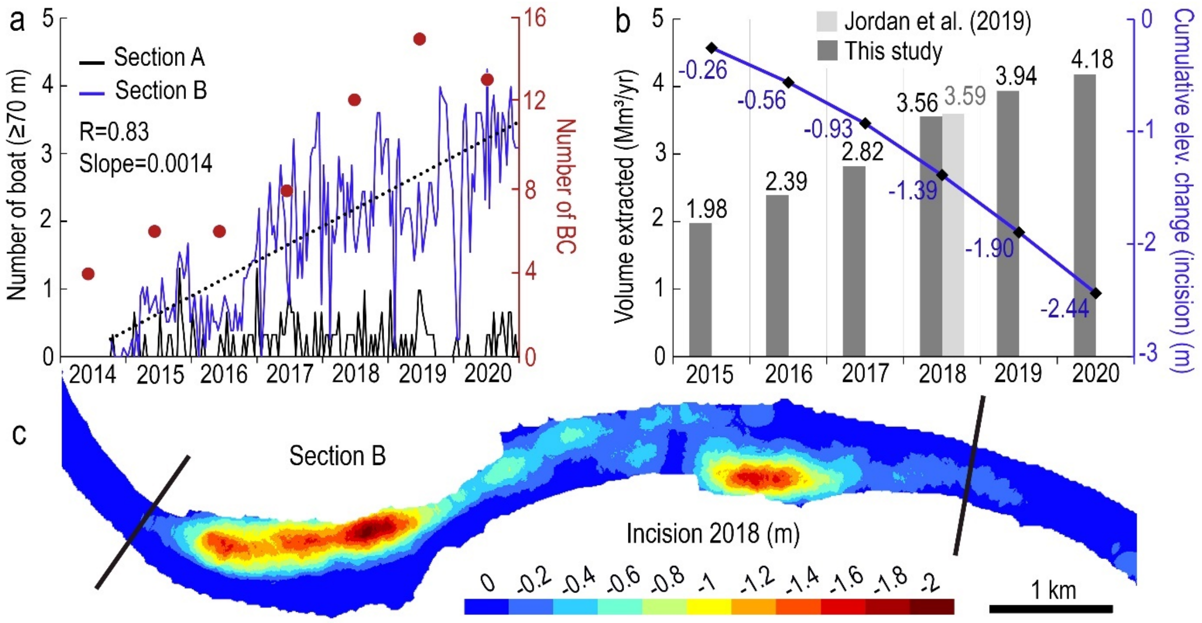


Fig. 4 Sand mining activity along the section A and B near Sà Dec. a: Number of boat ≥70 m /km^2 detected between Oct 2014 and Dec 2020 at 5.45 AM (descending orbit) on the section A and B. Number of BC observed along this reach per year (red) on Google Earth. Missing images 2018 correspond to the 2017-2019 mean. **b**: Volumes extracted between 2015 and 2020 in the section B and volume measured by Jordan et al. (2019) in 2018 on the same area (light grey). Cumulative incision along the section B in blue. **c**: Map showing the incision in 2018 along the section B (between km 6 and 15 in Jordan et al. 2019).

2.4. Illegal sand mining and official declarations

The sand mining budgets estimated in this study are 35% and 146% higher than those reported by Eslami et al.[20] and Jordan et al.[21], respectively. Comparative analysis in the different provinces with the results obtained by different authors highlight significant disagreements with the official declarations. We also remark that these estimations were likely to be underestimated in comparison with the values obtained from the official sources. Additionally, many documents (journal, scientific papers) have reported the recent intensification of illegal sand mining activities[10,27,28]. In this paper, the increasing number of BC observed from Google Earth that are located along the bank in the daytime after 2017 has effectively served as an indicator of potentially rampant mining. Other conflicting information also exists, for example, Koehnken and Rintoul[14] mentioned a single company (selling on internet) claimed that they could provide between 0.5 and 1 Mm^3 of sand from the VMD per month, i.e 12 Mm^3/yr. Yet in the same year, governmental institutions provided a total extraction budget of 17.7 Mm^3 to Jordan et al.[21]. Given that Bravard et al.[16] reported that there were about 39 sand mining operators on the VMD in 2012 and if the number of operators did not decrease over the next 6 years, we could expect that the volume declared for the region are grossly understated.

Jordan et al.[21] reported that sand mining (at least for 2018) was prohibited in the two provinces of Tiền Giang and Bến Tre, however 0.51 Mm^3 of sand extraction was revealed only from a small surveyed area of the Tiền Giang province[21]. Such studies imply that illegal mining is a continuing issue for the region. Similarly, the observation of the BCs from Google Earth showed a significant decrease of the activity in these provinces between 2015 and 2020 but not a complete disappearance. The number of BCs have entirely recovered in 2020. Given that the inter-provincial boundaries are mostly delineated by the mid-channel, the ill-defined boundaries and spatial shifting of the BC in these areas contribute the convenient conditions for illegal miners to work around loopholes in the laws, especially at night.

3. Conclusion

Although the VMD is one of the most intensively sand-mined area in the world, the existing sand mining budgets are limited by several technical and institutional barriers. Here we demonstrate a novel method based on physical measurements (bathymetry survey) and field-validated remote sensing data to quantify the past and present sand mining extraction over the entire VMD. Our results indicate that on average, 42 Mm^3/yr of sand is being extracted each year and this is causing incision of ~0.34 m (0.06 m/yr) across Vietnamese Mekong Delta (VMD) between 2015 and 2020. During this period, the levels of sand mining has increased by ~5% per year. The difference in reported values from local organization ranges from 35 to 146%. The Tiền River (including distributaries) represents 65% of the VMD area, however 83% of the VMD budget, while it was only 45% in 1998-2008. We speculate that the existing underestimations of the mining budgets are due to first, the limited methodologies, e.g., focusing on small geographical areas and second, reliance on the published statistics, which are likely either outdated and inaccurate. While the first reason relates to the instrumental barriers of the existing studies, other limitations are linked to an inability to police large areas and the prevalence of widespread of illegal mining activities that make it virtually impossible for the local governments to entirely manage and monitor the mining activities by current methods. Our method overcomes all the above limitations at very little cost. Our new budgets can also assist with the implementation of implement regulatory frameworks for sand mining to preserve a sustainable balance between natural supply and extraction. Finally, although the VMD was our test, our method can easily be implemented elsewhere where riverbed sand mining occurs extensively or where this activity is poorly defined or regulated.

Data and Method

Study area: The Vietnamese Mekong Delta (VMD)

The Vietnamese Mekong Delta (VMD) is the 3rd largest delta in the world with an area of nearly 100,000 km^2 and it has a channel area of ~875 km^2 is divided between two main branches, Hậu (Bassac) and Tiền (Mekong), which are connected by the Vam Nao channel. The annual VMD discharge is about 13,200 m^3/s at Kratie in Cambodia while monthly discharge varies between 1,600 and 37,000 m^3/s[29]. 75% of the Mekong's discharge originates from the Tiền R. upstream of the Vam Nao channel where it is split almost equally between Tiền and Hậu distributaries[22]. The hydrological regime is characterized by a dry season between November-May and a wet season between June-October that accounts for 80% of the total annual discharge is concentrated[29]. The VMD main channels traverse nine provinces in Vietnam partly separated each other by the mid-channel.

Field bathymetric surveys and the incision map

Bathymetric surveys were carried out using a Teledyne RD Instrument Workhorse Rio Grande 600 KHz Acoustic Doppler Current Profiler (ADCP) for 491 cross-sections in July 2014 and 380 in September 2017 (Supplementary Text 2). Along a 100 km reach in the Tiền Section (TS) area of ~120 km^2 [30] which starts 15 km downstream of the Cambodian border and ends around 2 km downstream of the Mỹ Thuận bridge, right before the channel bifurcation between the Mỹ Tho and the Cổ Chiên branches. The area includes the Vam Nao channel. We generated a bathymetry difference map (40 m resolution) resulting from a continuous accumulation and incision between 2014 and 2017. To minimize distortion in values due to outliers, we first averaged the bathymetry data using focal statistics. Thereafter, we filled gaps in the data using bilinear interpolation (5x5 window) to obtain a seamless incision map that constitutes ~15% of the whole VMD (98 km^2).

Boat classification system

Based on field survey realized in 2020-2021 and Google Earth images (2019-2020) observations, we found that the boats operating along the rivers of the VMD mostly range from lengths between 5-80 m. For our purposes, we only considered boats that are involved in sand mining. This allowed us to identify sand mining hotspots and estimate its intensity. Using high resolution Google Earth imagery (~0.5 m) during 2019-2020 we censed the entire pool of 1,150 boats along a 130 km reach along the Tiền River, and partly Cổ Chiên branch (Supplementary Fig. 3). To validate our boat classification system, we conducted a field survey along an 80 km reach in Tiền R. across 3 days (22nd December 2020 and 3rd and 15th January 2021). Sand mining hotspots were visited at the designated timings close to 5.45 AM and 6.11 PM, which coincide with the overpassing of the Sentinel-1A satellite imagery. The GPS coordinates of boats were recorded, and photos of individual boats were taken. This data was then compared against boats via Sentinel-1 imagery. The measurements from Google Earth imagery and field work allowed us to effectively target the sand mining barges. Our observations showed that Barges equipped with Crane (BC) have a specific pattern and are normally surrounded by numerous boats for sand transport in a randomized fashion. The randomized organization of the boats around the BC, their proximities, and the high frequency connection (cumulative length) appeared as a single large (~50% bigger) bright area in the radar image. Since our detection method was unable to distinguish the kind of boat and to separate these into individual boats a minimal length was used as criteria of detection.

Estimating sand mining budget of the VMD using remote sensing

We delineated the study area in the VMD using the Normalized Difference Water Index (NDWI) from the Landsat 8 Operational Land Imager (OLI) imagery between 2014 and 2020[31] (Supplementary Text 1). We applied a 0.1 DN threshold to delineate the water from land mass.

After removing non-channel areas such as canals, paddies, houseboats, bridges and ferry paths, we eliminated all areas within 50 m of the channel edge to minimize noise from non-active boats (used for sand mining or other purpose as well as parked along the channel bank, to remove any backscatter noise from constructions and non-boat recurrent detection. The areas surrounding the Cầu Vàm Cống bridge and Mỹ Tho and a small section of Cần Thơ were excluded from the analysis due to the high density of boats standing for commercial purpose and that are unrelated to sand mining extraction spot. We used the 20 m resolution Sentinel-1A (L1) imagery of descending orbit (n°18) Synthetic Aperture Radar (SAR) Ground Range Detected High resolution (GRD-H) C-band instrument (frequency of 5.405 GHz) dual polarization (VV+VH) that was acquired in Interferometric Wide (IW) mode with a 250 km swath (Supplementary Text 3). The whole VMD is covered at single swath on the same day (at 5:45 AM) at every 12 days since October 6, 2014, i.e., less than three months after our first bathymetry survey (Supplementary Fig. 2, Table 1). The advantage of SAR lies in its immunity against cloud cover, atmospheric phenomena, and sun elevation angle. SAR also has sufficient resolution for boat detection and showed high contrasts between water and the boat structures. The data is also publicly available from the European Space Agency (ESA) (https://scihub.copernicus.eu). As backscatter radar energy varies with many factors such as target shape, size, orientation, velocity, and material, it is crucial to select appropriate polarizations[32,33]. Whilst scientific literature has reported that VH cross-polarization is optimal for boat detection, our results have shown that VV polarization shows a much better correlation between boats detected and the bathymetry difference dataset.

We first processed all Sentinel-1A (both ascending and descending) images available (N=293) in the VMD between October 6, 2014 and December 22, 2020 (see full method in supplementary Text, Fig. 1). These images were pre-processed with radiometric, geometric calibration, removal thermal noise and georeferenced in WGS84, using the ESA SeNtinel Applications Platform (SNAP) (https://step.esa.int/main/toolboxes/snap). After visual inspection and simulations, we applied a 0.5 threshold to the scattering coefficient (γ^0) to each image, which was then converted into a binary raster. This was done to filter out noise, separate boats that are close to each other and removing smaller boats. The resultant raster was cropped using the VMD study area channel mask. After vectorizing the extracted boats (backscattered boat surface), we calculated the quantitative statistics for main features such as lengths and areas. Thereafter, we extracted the center of each boat as a point. Using only the descending orbit data, we conducted multiple simulations alongside field data. These simulations showed that a threshold of ≥70 m boat length was optimal and was able to match relatively well with the incision areas. The boats with a length ≥ 70 m were selected per year and then per period each year corresponding (i.e., Oct 2014 to Dec 2017). Then, we generated a 10 m resolution boat density map and defined a 200 m radius buffer after comparison with different radius (from 100 to 300 m). Heat maps showing boat density (number of boats per km^2) were normalized by dividing the raster values by the number of images in the period (91 images from 2014-2017). Finally, the heatmap was resampled to 40 m to match the resolution of bathymetry difference map and converted into points (N=61,663). Corresponding values between bathymetry and boat density were plotted and the median bathymetry difference at each 0.1 boat density beam was calculated. A regression equation was derived from this. Thereafter we used boat density per day (1 image every 12 days), normalized every 3 years to estimate incision rates and the volume of sand extracted from the regression equation at the VMD scale. This method was applied to every year between 2015 and 2020 in three-year intervals (i.e., unique values for 2015-2017, 2016-2018, etc.) Thereafter, we average overlapping values to find an average value for each year. For example, there are 3 values for the year 2017 (2015-2017, 2016-2018 and 2017-2019); these 3 values were average to obtain a single value for 2017 (Supplementary Table 3). To our results with institutional declarations (Supplementary Text 4 and 5, Table 6 and 7), we calculated the volume of sand extracted in the different provinces using the administration borders scattering provided by Humanitarian Data Exchange (HDX) (https://data.humdata.org).

To evaluate the validity of the relationship between boat density and intensity of sand mining, we mapped all the barges that were equipped with at least one crane (BC) across the VMD between 2014 and 2020 using one image per year on Google Earth. When there was a missing year, we used images from +/-1 year. Then we measured the boat density per km^2 (200 m radius) of each boat ≥70 m (N=42,054) and their distance with the nearest BC (N=1,181) on the VMD study area for the period 2014 to 2020. Images used were of descending orbit. Boat (length ≥70 m) number and their evolution has also been investigated at the whole VMD scale between 2014 to 2020 using data from both ascending and descending orbits. Two reaches located along the TS were analyzed. Section A (7.2 km) was chosen because it is located on the mainstream of Tiền River and was observed to have a lower boat density (absence of sand mining activity) during the study period (Fig. 4). Whereas section B (9.4 km) is located near Sa Đéc, which is a sand mining hotspot which was previously studied in April-May 2018 by Jordan et al.[21]. We sampled our results in the same reach between 2015 and 2020 and compared our values against theirs. Values from different publications which focused on specific reach and periods were also compared in time and space at the VMD scale.

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Authors contribution

CRG: Conceptualization, method, data acquisition, processing, data analysis, writing; EP: Conceptualization, method, writing, supervision, funding; HHL: Conceptualization, method, writing; SK, LF, DVB: method, data acquisition, writing; ADZ: Conceptualization, method, writing, supervision, funding.

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