International Journal of Applied Earth Observations and Geoinformation 108 (2022) 102736

Contents lists available at ScienceDirect

International Journal of Applied Earth Observations and Geoinformation

journal homepage: www.elsevier.com/locate/jag

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

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ARTICLE INFO

Keywords:
Sand mining
Riverbed incision
Remote sensing
Mekong Delta
Sustainability

ABSTRACT

The river beds of the Mekong Delta are some of the most intensively sand mined places in the world. However, sand mining budgets remain limited to rough and indirect estimates. Here, we provide a first systematic, field-based estimation of the Mekong Delta's sand mining budget. This budget overcomes the limitations of relying on officially declared statistics and bathymetric surveys of short channel reaches. We applied 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 which were derived from two extensive bathymetric surveys conducted in 2014 and 2017. The two surveys cover ~ 100 km in the Tiền River, reaching approximately 15% of the Mekong Delta. We then extrapolated the Tiền River findings to the broader Vietnamese Mekong Delta from 2015 to 2020 and measured a continuous increase of the extraction budget by ~ 25% between 2015 (38 Mm^3/yr) and 2020 (47 Mm^3/yr). We estimated 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 field-based annual rates are higher than both official declarations provided and estimates from previous studies which implies that a substantial portion of the sand mining budget remains unaccounted for. Riverbed sand mining remains a key threat to the Mekong Delta as it contributes to a multitude of other environmental threats including dam construction effects on sedimentation, ongoing subsidence, sea level rise and recurring saltwater intrusion. This study offers a new approach that can be implemented elsewhere to allow for systematic monitoring and quantification of sand mining activities that are vital for assessing future projections on environmental impacts.

1. Introduction

Rising sand demand for construction and land reclamation, fueled by rapid population and economic growth in Asia, has resulted unprecedented rates of riverbed sand mining (de Leeuw et al., 2010; Dan Gravriletea, 2017; Torres et al., 2017; UNEP, 2019; Best, 2019) in recent decades. Riverbed sand extraction is commonly unregulated in much of south and southeast Asia and the quantities and impacts remain largely hidden as the operations are submerged. However, river sand is a finite resource and it must be properly managed to avoid adverse alterations to river hydrology that can trigger irreversible transformations to the natural and social-ecological systems. These transformations can compromise livelihoods and cause significant deterioration to local ecosystem services (Kondolf, 1997; Kondolf et al., 2014; Loc et al., 2017; Lamb et al., 2019).

Sand mining has both short- and long-term consequences. Short term sand mining impacts include bank erosion, bed incision, and groundwater table modifications while in the long run, sand mining can compromise delta-wide water supply resources, intensifie saline water intrusion, and reduce floodplain connectivity (Kondolf, 1997; Torres et al., 2017; Beiser, 2018; Park et al., 2020; Park et al., 2021; Loc et al., 2021). Despite these well-known consequences, the study of sand

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https://doi.org/10.1016/j.jag.2022.102736
Received 21 September 2021; Received in revised form 11 February 2022; Accepted 28 February 2022
Available online 21 March 2022
1569-8432/

mining is limited by a lack of regional data on extraction budgets that is primarily driven by a desperate absence of effective monitoring systems (Peduzzi, 2014).

Illegal or unregulated sand mining has been a global problem (Koehnken and Rintoul, 2018). This is particularly worrying in Asia in countries like Vietnam, Cambodia, and Laos where there is an evident lack of regulatory frameworks and licensing, along with inefficient monitoring (Nguyen, 2011; Bravard et al., 2013; Koehnken and Rintoul, 2018; Koehnken et al., 2020). Since large-scale operations started in the 1990 s, the Vietnamese Mekong River has been heavily impacted by significant riverbed dredging (Bravard et al., 2013). Sand mining in the Mekong is primarily carried out by mechanical shovels on barges that feed a fleet of boats and barges. Dredging operations tend to stay within the same concession area until the area is exhausted or the extraction license expires (Ng and Park, 2021).

In Vietnam, licensing was decentralized in 2005, changing from the national to provincial level, which resulted in an exponential increase in the number of mining licenses issued (Schiappacasse et al., 2019). The decentralization has also severely inhibited the ability to determine the exact number and operational capacity of businesses in operation. This is likely due to limitations on human resource and technical capacity in provincial governments, as well as limited coordination among the relevant departments (Schiappacasse et al., 2019). The Vietnamese government predicted demand for sand from riverbed to be 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 (SIWRP, 2015; Koehnken and Rintoul, 2018; Eslami et al., 2019). 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 (Jordan et al., 2019). As a result, not only assessing the environmental impacts caused by riverbed sand mining activities is complicated by the immense scale and dynamic environment, it is also made more complex by the limited regulatory power in the affected countries. There is, thus, 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 into the environmental discourses. In the Vietnamese Mekong Delta (VMD) area, notable attempts in quantifying the mining budgets include Bravard et al. (2013) who surveyed extractors and provided an overview of the riverbed mining intensities along the Mekong; Brunier et al. (2014) who analyzed a VMD bathymetry dataset between 1998 and 2008 and further highlighting the impacts of the excessive sand extraction; Anthony et al. (2015) who went beyond surveys to link the shoreline erosion of the delta to riverine sand extraction; and Eslami et al. (2019), where they analyzed the amplified salt intrusion partially driven by the intensive riverbed mining.

For budgeting approaches, Jordan et al. (2019) 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, though the budgets are mostly based on official declarations. In Cambodia, Hackney et al. (2020, 2021) have focused their work on bank instability related to sand mining and measured an inferred sand budget using PlanetScope imagery. However, these attempts to estimate sand extraction values are either locally estimated (Jordan et al., 2019) which is only reflective of particular periods (Brunier et al., 2014), or based on incomplete or inaccurate official declarations (Bravard et al., 2013; Eslami et al., 2019). Instead, estimates are complicated by the 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 field-based 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 the final step the mathematical relationship was applied to the entire ~ 700 km^2 of the VMD (selected area in this study) to construct an annual sand mining budget and calculate incision rates between 2015 and 2020. Our new budgets were then compared geographically and historically with the previous estimations from different publications.

2. Data and method

2.1. Study area: The Vietnamese Mekong Delta (VMD)

The Mekong Delta is the 3rd largest delta in the world and and an area of 40,000 km^2 lies within the Vietnamese borders. The channel area of ~ 875 km^2 (but 700 km^2 analyzed in this work) is divided between two main branches, Hậu (Bassac) and Tiền (Mekong), which are connected by the Vam Nao channel. The annual VMD discharge at Neak Luong and Koh Kehl (Cambodia) is about 13,000 m^3/s. 75% of the Mekong's discharge originates from the Tiền river upstream of the Vam Nao channel where it is split almost equally between Tiền and Hậu distributaries (Brunier et al., 2014). 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 (MRC, 2019). The VMD main channels traverse nine provinces in Vietnam, partly separated by the mid-channel (Fig. 1).

2.2. 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). The area of TS is estimated to be 120 km^2 (Binh et al., 2020), starting 15 km downstream of the Vietnam-Cambodian border and ending 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).

The VMD is affected by different fluvial processes. The presence of dams reduces sediment supply, creating gentle slopes, as erosion and lateral mobility are kept relatively low. The bathymetry difference obtained here corresponds to about 15% of the whole VMD channels (98 km^2) approximates to an average incision per year and corresponds to several high-water and low-water seasons with small sediment supply and deposition balanced out each year. Hence the bathymetry difference used in this study is considered to approximate the incision depth dominantly due to sand mining activities.

2.3. Boat classification system

Based on a field survey made in 2020–2021 and Google Earth images (2019–2020) observations, we found that the length of boats operating along the rivers of the VMD range between 5 and 80 m. For our purposes, we only considered boats that are involved in sand mining which can be easily distinguishable by their pattern, the presence of sand on it and their clustered organization. This allowed us to identify sand mining hotspots and estimate its intensity. Using high resolution Google Earth

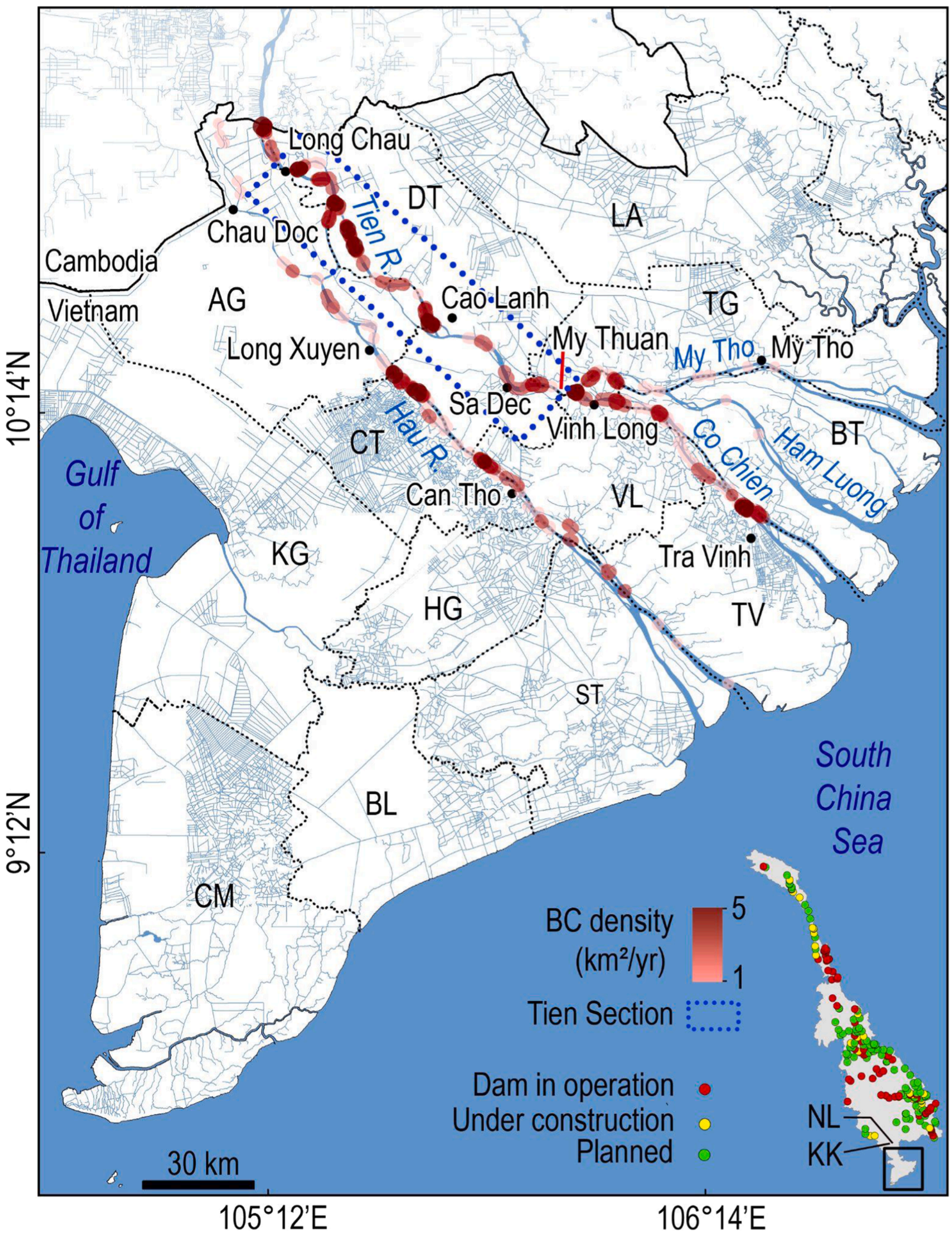


Fig. 1. Map of the Vietnamese Mekong Delta displaying barge with crane distribution and density and inset map corresponds to the Mekong basin showing dams (Mekong River Commission), KK = Koh Kehl station, NL = Neak Luong station. The Tiền Section (TS) corresponding to the bathymetry survey is delineated within the blue dotted rectangle. Black dots correspond to the main riparian cities. Upper and lower Tiền R. are separated at the Mỹ Thuận arrow. AG = An Giang, BL = Bạc Liêu, BT = Bến Tre, CM = Cà Mau, CT = Cần Thơ, DT=Đồng Tháp, HG = Hậu Giang, KG = Kiên Giang, LA = Long An, ST = Sóc Trăng, TG = Tiền Giang, TV = Trà Vinh, VL = Vĩnh Long (Sources: OpenStreetMap, Humanitarian Data Exchange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

imagery (~0.5 m) during 2019–2020, we censed the entire pool of 1,150 boats along a 130 km reach stretches along the Tiền River, and part of the Cổ Chiên branch. 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 days around 5.45 AM and 6.11 PM, to 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. The randomized positions of the boats around the BC, their proximities, and high frequency connection (cumulative length) appeared as a single large (~50% bigger) bright area in the radar images. Since our detection approach was unable to distinguish the type of boat and separate individual boats, a minimal length was used as criteria of detection.

2.4. 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. To obtain an average extent of the channels, one image was retrieved per year between 2014 and 2020 (McFeeters, 1996) (Supplementary Text 1) and merged due to difficulties in retrieving cloudless images. 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. Based on Google Earth images interpretations, 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 that were 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) instrument in dual polarization (VV + VH) that was acquired in Interferometric Wide (IW) (Supplementary Text 3). The whole VMD is covered at a single swath on the same day (at 5:45 AM), at every 12 days since October 6, 2014, i.e., less than two months after our first bathymetry survey (Supplementary Fig. 1, Supplementary 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. As backscatter radar energy varies with many factors such as target shape, size, orientation, velocity, and material, it is crucial to select appropriate polarizations (Kurekin et al., 2019; Lanz et al., 2020). 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). These images were pre-processed with radiometric, geometric calibration, removal thermal noise and georeferenced in WGS84, using the ESA SeNtinel Applications Platform (SNAP). After speckle filtering test, visual inspection and simulations, we finally applied a 0.5 threshold to the scattering coefficient (γ^0) to each image for removing pixels artifacts. Later, we converted the selected pixel clusters into a binary raster. This was done to filter out noise, separate boats that were close to each other and to remove smaller boats. The resultant raster was cropped using the VMD study area channel mask. After vectorizing the extracted boats (backscattered boat surface), we automatically measured the 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 to discriminate boats for sand mining from other boats. These simulations showed that a threshold of ≥ 70 m boat length was optimal to match with the incision areas. These boats (≥70 m) were selected per year and then per period of each year (i.e., Oct 2014 to Dec 2017). We then generated a 10 m resolution boat density map and defined a 200 m radius buffer after simulations with different radii (100–300 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 to 2017). Finally, the heatmap was resampled to 40 m to match the resolution of the 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. 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 approach 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 averaged overlapping values to attain an average value for each year (workflow is illustrated in Fig. 2). For 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.

As for validation 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 years were missing, we used +/-1 year. We then measured the boat density per km^2 (200 m radius) of each boat ≥ 70 m in descending orbit (N = 42,054) and their distance with the nearest BC (N = 1,181) on the VMD for the period 2014 to 2020. Boat (length ≥ 70 m) number and their evolution has also been investigated at the whole VMD scale between 2014 and 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. 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. (2019). 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.

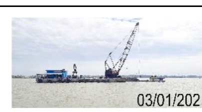
3. Results and discussion

3.1. Sand mining boat activity and hotspots

Observations on Google Earth images of 2019–2020 showed that Barges with cranes (BC) that are used for sand extraction constitute 10% of all boats associated with sand mining (Table 1, 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, of which 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 (Fig. 3). While it is impossible to

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

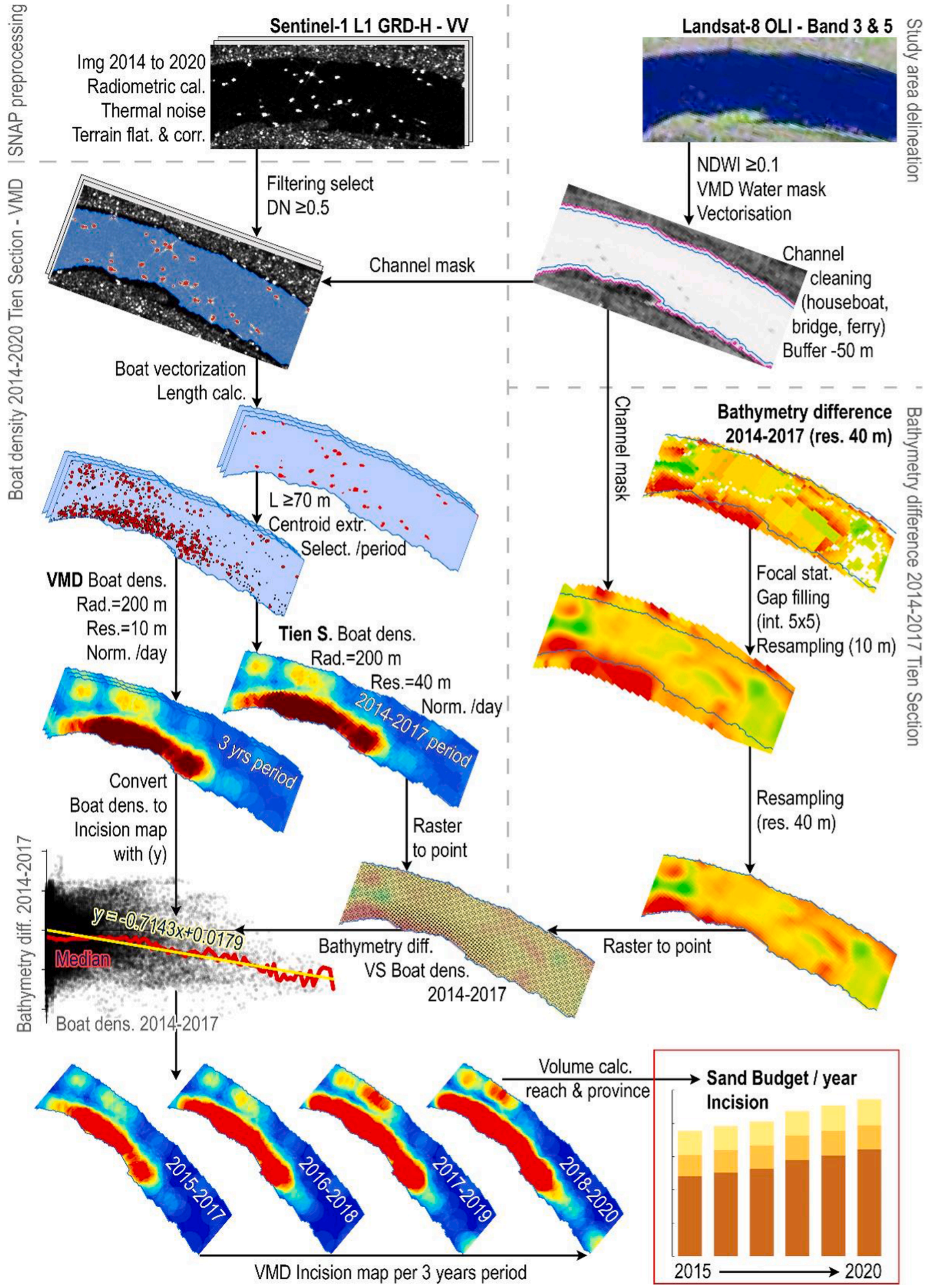


Fig. 2. Methodological flowchart illustrating the calculations of the sand budget and the riverbed incision based on Sentinel-1 SAR and bathymetry difference. (Copernicus Sentinel data 2020, processed by ESA).

distinguish between BB and BT using length, the BC, which represents the core of sand extraction activity, is distinctive. However, single BC only occurred 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 were 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.

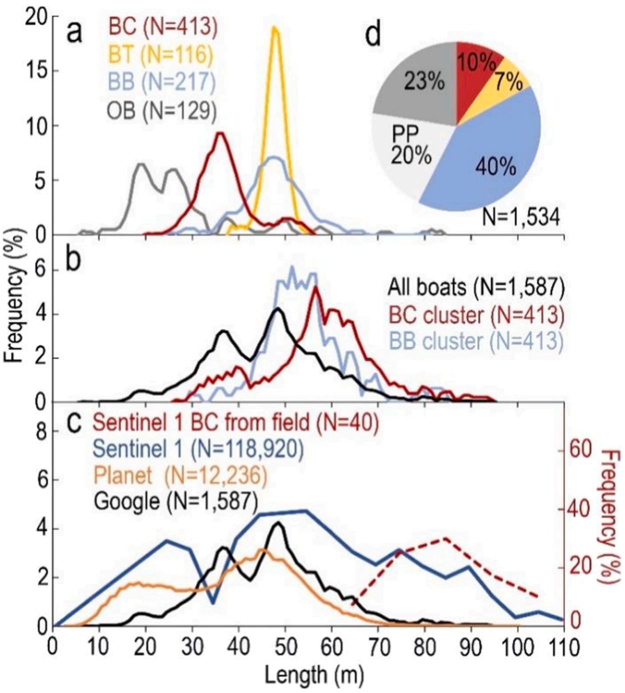


Fig. 3. Boats size and distribution per kind. **a:** Length range and frequency of the BC, BT, BB and OB on Google Earth. Moving average values (period = 3) are displayed. **b:** Length range and frequency of all the single and boats clusters, length of the BC clusters and BB cluster from Google Earth. Moving average values (period = 3) are displayed. **c:** Length range and frequency of all the single and coupled boats from Google Earth, Boats measured on PlanetScope images, Boats detected from Sentinel-1 SAR and length from Sentinel-1 of BC observed and localized on the field. Moving average values (period = 3) are displayed except Sentinel-1. **d:** Distribution of the different kinds of boat on the VMD.

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% in 2015 to 125 BCE before increasing gradually to 185 BCE in 2020 (Fig. 4). 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 slightly, with little changes after 2016. The total number of BC located in the channel were similar in 2015 and 2016, but this difference increased from 12 to 22 between 2017 and 2020. 7% of the BC within the VMD observed between 2014 and 2020 were not located in the study area, but along the bankside; this implies that they might have been parked or potentially used at night instead.

75% of the 244 BCE 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 rise of the incision with an increase in parallel boat density. By 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. 4). About 50% of the boats were located less than 224 m away from 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 represents only 11% of the whole VMD area.

Our sand mining boat density map over the VMD showed large spatial variability. We identified several major sand mining hotspots along the Cambodian border on the Tiền River (Supplementary Figs. 2 and 3). Intensive extraction sites were also found around Long Khánh Island, the channel heading towards the Vam Nao, Thuận Đông Island and around Sa Đéc. Downstream of Mỹ Thuận, the major hotspot was detected around the Mỹ Tho and Cổ Chiên confluence, near Vĩnh Long city and around An Phước. The most downstream hotspot was downstream of the Co Chien bridge. On the Hậu River, the concentration of sand mining boats 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 were 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 represent 11% and 20% of the hotspots respectively, with a smaller average area of 0.08 km^2.

3.2. 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. 5). 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

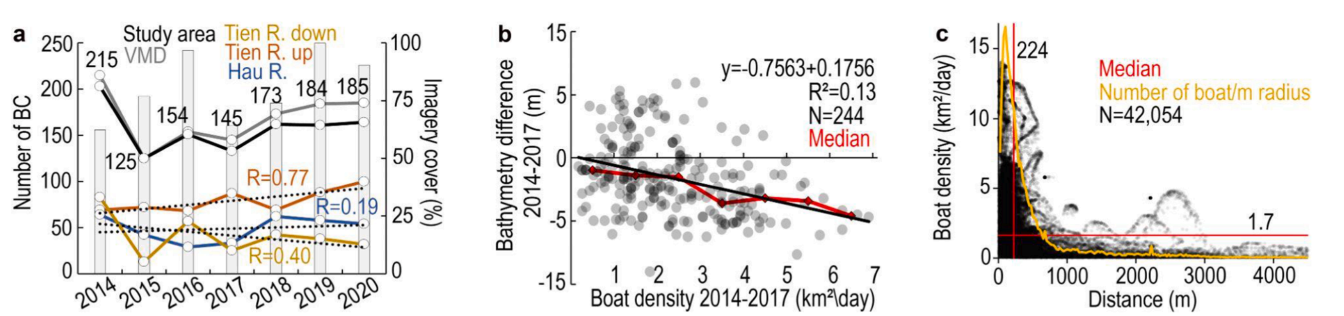


Fig. 4. Barges with crane number, distribution and distance with boats detected with Sentinel-1 between 2014 and 2020. **a**: Evolution of the BC number over the period 2014–2020 in the VMD and in-channel study area, Tiền River: upstream and downstream, Hậu River. Histograms represent the proportion of Google Earth cover over the VMD per corresponding year and the black box to the VMD location. **b**: Median boat density (x) and the median of bathymetric difference surrounding the 200 m radius of each BC in the TS. **c**: Graph showing in × the distance between all boats (≥70 m) with the nearest BC (distance max 4,500 m). In y the density of boats surrounding each of these boats. The orange curve corresponds to the BC-Boat distance (m) frequency. The two red lines correspond to the × and y median. The wave shape between 1,000 and 3,000 m corresponds mostly to the part of the channel where BC might have been present, but Google Earth images were missing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

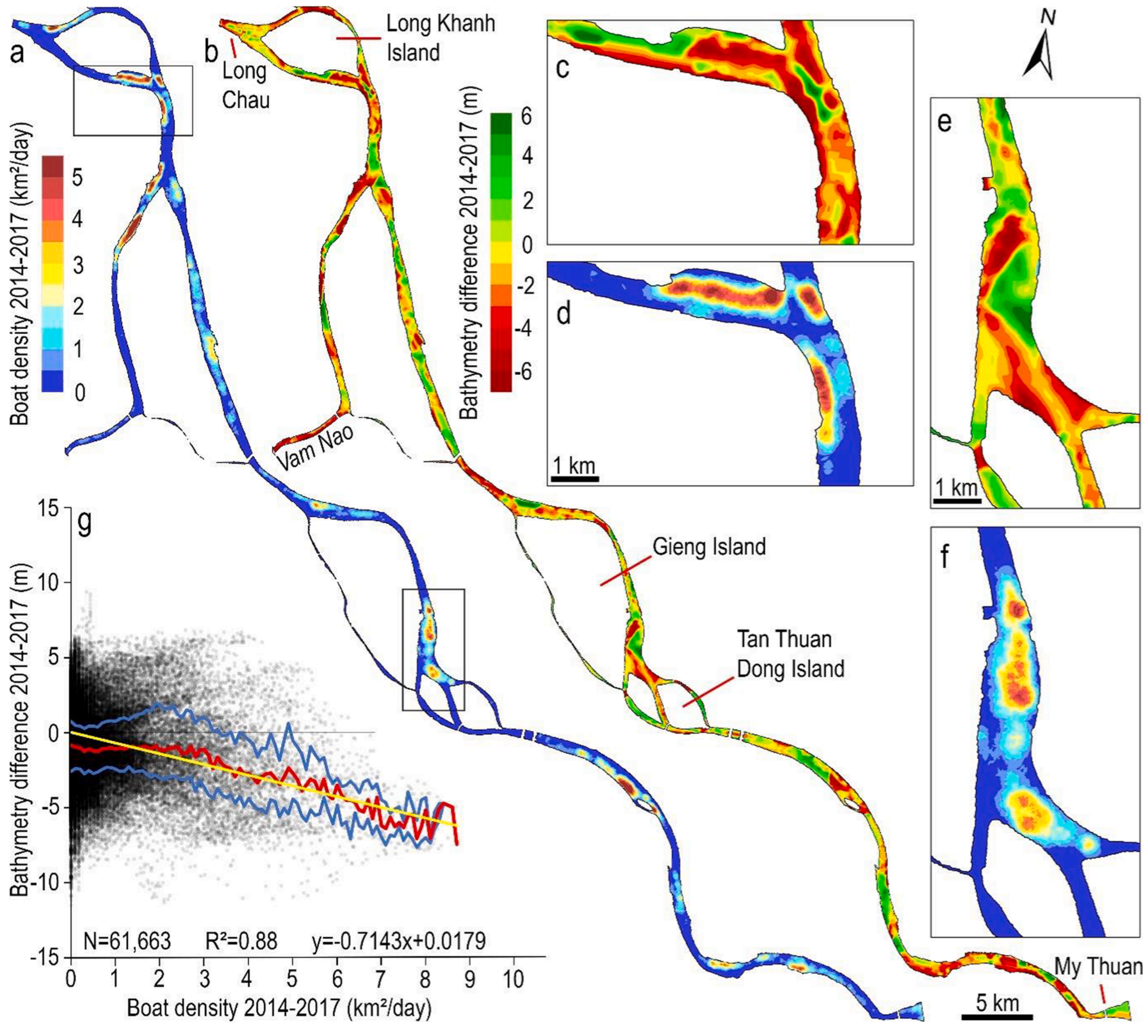


Fig. 5. Bathymetry difference and boat density along the TS. **a**, **d**, **f**: Boat density/km^2 2014–2017. **b**, **c**, **e**: Bathymetry difference 2014–2017. **g**: Boat density 2014–2017 versus Bathymetry difference 2014–2017 plotting at resolution 40 m. Blue lines correspond to Q1 and Q3, red line is the median of the bathymetry difference at each 0.1 boat density beam. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 and 3 (Fig. 5). The slope of the linear regression model derived between bed incision and the boat density was statistically significant at 95% (p-value less than 0.001). Beyond the threshold of 3 boats/km2, 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 in boat density of ~ 32% of the average (from 0.85 to 1.13 /km^2). However, 47% of regions with 3 or more boats in 2014–2017 had reduced densities of boats (less than2 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.

We calculated that a total amount of 253.58 Mm^3 of sand was extracted in the VMD during the period 2015–2020, with an average of 42.26 Mm^3/yr (Fig. 6, Supplementary Table 2 to 5). The most intensively mined area lies upstream of Mỹ Thuận on the Tiền River and had 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 a 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 between 2015 and 2020 has continuously increased 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) (Fig. 6). 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 respectively. The period 2018–2019 and 2019–2020 showed increases of 1.62 Mm^3 and 2.03 Mm^3, respectively (Supplementary Table 2). This increasing trend is primarily due to extraction in the upper Tiền River, which was observed to have a constant increase (34% between 2015 and 2020) in the volume of sand extracted. Sand extractions peaked in 2017 to 2018, amounting to 2.71 Mm^3 (inter-annual difference in mean 1.62 Mm^3).

Downstream of Mỹ Thuận (inter-annual difference in mean 0.16 Mm^3) experienced 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, we imply that the entire VMD experienced a total incision of 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. that reaches up to the Cambodian border, experienced the

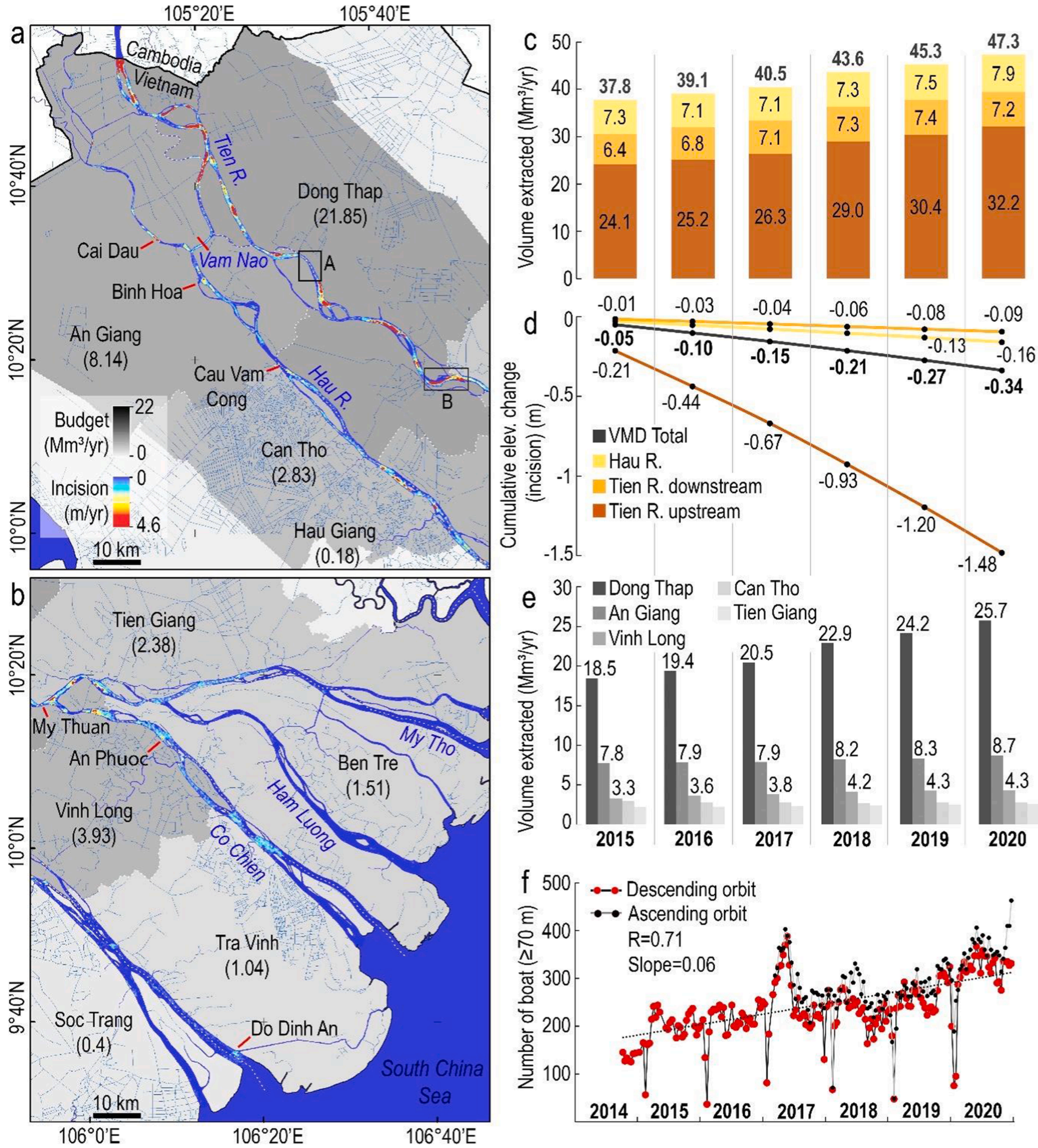


Fig. 6. Volume extracted, incision rates and boat activity. **a**, **b**: Map showing the sand mining hotspots and the average incision on the VMD. The province scattering from HDX and the average sand mining budget per province displayed in grey intensity. The 3 studied sections of the VMD (Upper and 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. 7, 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 (in dark grey at the top). **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 ($\geq$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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deepest incisions of approximately 1.48 m in 6 years with an annual average rate of 0.25 m. In the Hậu R. we infered an incision of 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. (2014) 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 and 2020. More recently, Binh et al. (2021) 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.

From 2015 to 2020, the density of boats of $\geq$ 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 from 0.72 to 1.54 boat/km^2. In contrast, the lower Tiền R. showed 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 an average of about 0.2 boat/km^2 at 5.45

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

AM (morning) and 0.5 boat/km^2 at 6.10 PM (evening) (Figs. 6 and 7). In section B, however, the difference between morning and evening orbits was less significant, with difference of about 0.1 boat/km^2.

3.3. Budget and incision comparative analysis

Published sand mining budgets for the VMD, are primarily focused on either specific geographical area of the delta (Jordan et al., 2019) or relied on the official statistics (Eslami et al., 2019; Jordan et al., 2019). A regional sand mining budget of the VMD was estimated by Bravard et al. (2013), 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). Calculations by Bravard et al. (2013) equates to approximately ~8.5 Mm^3 in total if we extrapolate their value to our entire study area. Later, Brunier et al. (2014), based their work on the bathymetry difference between 1998 and 2008 along part of the Hậu and Tiền Rivers, and claimed that an average of 20 Mm^3/yr, i.e., 35.5 Mm^3/yr of extraction occurred along the whole VMD. More recently, Eslami et al. (2019) and Jordan et al. (2019) estimated the budgets of 28 Mm^3 (2015) and 17.77 Mm^3 (2018), from the licenses issued and governmental institutions. Though they

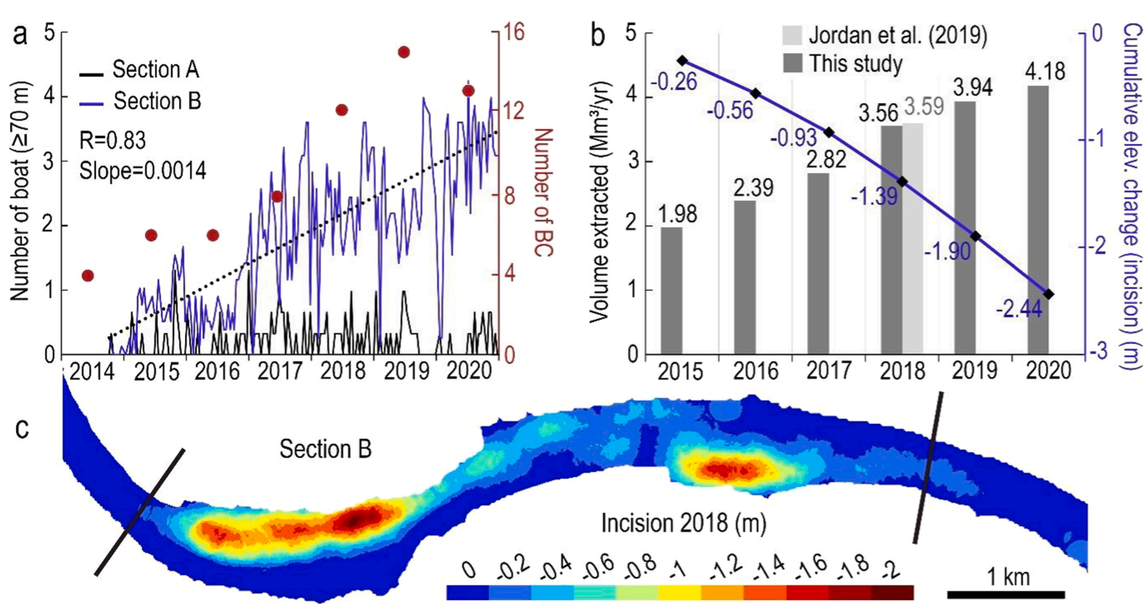


Fig. 7. Sand mining activity along the section A and B near Sà Dec. **a**: Number of boat ≥ 70 m /km^2 detected between Oct 2014 and Dec 2020 at 5.45 AM (descending orbit) on the section A and B. Number of BC observed along this reach per year (red) on Google Earth. Missing images in 2018 correspond 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 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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

refer to two different years, these last two references extrapolate to 28 Mm^3/yr and 22 Mm^3/yr at the VMD scale (Table 2). We calculated an extraction volume of 37.8 Mm^3 for 2015. This is 35% more than the value provided by Eslami et al. (2019). More significantly, our estimation of 43.6 Mm^3 in 2018 is 2.5 times higher than the values by Jordan et al. (2019). For the period 1998–2008, Brunier et al. (2014) reported more sand mining on the Hậu River (55%) than on the Tiền River. However, our calculation revealed that only 17% of the VMD extraction from the Hậu River corresponds to 20% of the hotspots between 2015 and 2020.

According to Jordan et al. (2019), 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. (2019) 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) indicated that their estimated rate of Tiền Giang in 2018 was likely to be under-estimated, which is in line the re-estimated value of 2.42 Mm^3/yr in this study. Similarly, we estimated the rate of 1.51 Mm^3/yr in Bến Tre (1.57 Mm^3 in 2018), as several BCs were clearly visible on the respective Google Earth image.

Between April and May of 2018, Jordan et al. (2019) estimated an extracted volume of 3.59 Mm^3 along a 10 km reach (km 6 to 15 in Jordan et al. (2019)), near Sa Đéc. Chronological observations of BC from Google Earth, coupled with detections by Sentinel-1, showed that sand mining along this section might have started after 2015 (Fig. 7a). The activity became 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. (2019). The numbers of BCs detected in 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 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 estimation. In the same year, field measurements by Jordan et al. (2019) showed that 3.59 Mm^3 of sand was extracted in 8 pits that were $\geq$ 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.

3.4. 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. (2019) and Jordan et al. (2019), 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 (Beiser, 2018; Bendixen et al., 2019; Duan et al., 2019). In this paper, the increasing number of BC observed from Google Earth that are located along the bank in the daytime after 2017, effectively served as an indicator of potentially rampant mining. Other conflicting information also exists, for example, Koehnken and Rintoul (2018) 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. (2019). Given that Bravard et al. (2013) 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. (2019) 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 (Jordan et al., 2019). 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 halt. The number of BCs had entirely recovered by 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 to the convenient conditions for illegal miners to work around loopholes in the laws, especially at night.

4. 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 approach, based on the correlation of 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 an incision of $\sim$ 0.34 m (0.06 m/yr) across Vietnamese Mekong Delta (VMD) between 2015 and 2020. During this period, the level of sand mining has increased by $\sim$ 5% per year. The difference in reported values from local organizations ranges from 35% to 146%. The Tiền River (including distributaries) represents 65% of the VMD area, accounting for 83% of the VMD budget, although 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 illegal mining activities that make it virtually impossible for the local governments to entirely manage and monitor the mining activities. Our approach overcomes all the above limitations at very little cost. Our new budgets can also assist with the implementation of improved regulatory frameworks for sand mining to preserve a sustainable balance between natural supply and extraction. Finally, although the VMD was our test, our approach can easily be implemented elsewhere where riverbed sand mining occurs extensively or where this activity is poorly defined or regulated.

CRediT authorship contribution statement

Charles-Robin Gruel: Conceptualization, data processing and analysis. **Edward Park:** Conceptualization, Supervision, Funding. **Adam D. Switzer:** Conceptualization, Supervision, Funding. **Sonu Kumar:** . **Huu Loc Ho:** Conceptualization, Data collection. **Sameh Kantoush:** Data collection and processing. **Doan Van Binh:** Data collection and processing. **Lian Feng:** Conceptualization.

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.

Acknowledgments

This study is funded by Nanyang Technological University (#SUG-NAP 3/19EP) and Ministry of Education of Singapore (#Tier1 RT06/19,

#Tier1 2021-T1-001-056 and #Tier2 MOE-T2EP402A20-0001). The authors also acknowledge Japan-ASEAN Science, Technology and Innovation Platform (JASTIP), and the Supporting Program for Interaction-based Initiative Team Studies (SPIRITS 2016) of Kyoto University. We acknowledge the European Space Agency (ESA) for supplying Sentinel-1 data used in this study. We would like to thank Jana Lim for technical assistance. This research was supported by the Earth Observatory of Singapore via its funding from the National Research Foundation Singapore and the Singapore Ministry of Education under the Research Centres of Excellence initiative. This work comprises EOS contribution number 436.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jag.2022.102736.

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