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Extent of illegal sand mining in the Mekong Delta

Kai Wan Yuen [1,2], Edward Park [1,2✉], Dung Duc Tran[2,3], Ho Huu Loc[4], Lian Feng [5], Jingyu Wang[2], Charles-Robin Gruel[1,6] & Adam D. Switzer [1]

Sand is a vital ingredient for modern structures and to meet demand, a substantial volume of sand is extracted illegally from riverbeds globally. The Vietnamese Mekong Delta is one of the largest delta in Asia and it has a long history of riverbed sand mining. We quantified the illegal sand mining rate in this major sand mining hotspot, as the difference between the actual volume of sand mined and the allowable rate of sand extraction set by the provincial government. The volume of illegally mined sand decreased from 16.7 Mm^3/yr in 2013 to 15.5 Mm^3/yr in 2018-2020. An increase in the allowable rate of sand extraction from 11.5 Mm^3/yr to 15.1 Mm^3/yr reduced the volume of illegally mined sand. We recommend that scientific research should be conducted to assess the allowable rates of sand extraction and the volume of sand reserve.

[1] Earth Observatory of Singapore (EOS) and Asian School of the Environment (ASE), Nanyang Technological University (NTU), Singapore, Singapore. [2] National Institute of Education (NIE), Nanyang Technological University (NTU), Singapore, Singapore. [3] Center of Water Management and Climate Change (WACC), Institute for Environment and Water Resources (IER), Vietnam National University, Ho Chi Minh City, Vietnam. [4] Water Systems and Global Change Group (WSG), Wageningen University and Research, Wageningen, Netherlands. [5] School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China. [6] Centre National de la Recherche Scientifique (CNRS), Paris, France. ✉email: edward.park@nie.edu.sg

Sand is a critical mineral resource and its importance for socio-economic development is reflected in the fact that the volume of sand extracted globally exceeds the amount of fossil fuels and biomass extracted[1]. 32–50 billion tonnes of sand and gravel are excavated from riverbeds, beaches, and quarries annually, mostly to produce concrete, asphalt, glass and electronics[2,3]. Sand is also needed for landfill and reclamation[4,5]. To match demand, the volume of sand extraction often exceeds the rate of natural renewal[5] with serious environmental consequences. The impacts of riverbed sand mining include increased channel incision, bank instability, lowered riverbeds, reduced flood frequencies and increased saltwater intrusion[6–9]. Meanwhile, mining beaches increases coastal erosion which damages infrastructure[3,10]. To address the environmental damage created by sand mining, the United Nations had issued resolutions on Mineral Resource Governance such as UNEA 4/19 and UNEA 5/12 to highlight and deal with this emerging problem[11,12].

High demand for sand by the construction industry and the lucrative nature of the sand trade may incentivize mining operators to flout the law and mine illegally to meet demand and maximize profits. Regulations established by the authorities to manage sand mining include the need to have a valid sand mining license to carry out mining operations, only mining within permitted mining areas and extracting a fixed amount of sand. However, the vast area, coupled with limited resources and sometimes ambiguous policies mean that the local authorities have little or no ability to detect and punish illegal mining[13–15]. In addition, illegal mining persists as it is often associated with organized crime with the police on the side of the illegal miners[16]. Arguably, government crackdowns and strict monitoring can eradicate illicit activities but as soon as enforcement efforts and policies against illegal mining are relaxed, there may be a resurgence of illegal mining[17,18]. As quantitative data to differentiate between legally or illegally mined sand is lacking, existing research on illegal mining have focused on the reasons behind illegal mining instead. Overall, the prevalence of illegal mining suggests that a lot more sand was being extracted than officially allowed[19].

Southeast Asia (SEA) is a major sand mining hotspot, and sand is being stripped illegally from many riverbeds in the region[20,21]. We used the Vietnamese Mekong Delta (VMD) as a representative case study for highlighting the issue of illegal mining globally as it is one of the largest delta in Asia and it has a long history of intensive and illegal riverbed mining that has left clear environmental footprints[22]. In addition, similar to other megadeltas around the world, the VMD is a major agriculture production hub facing multiple anthropogenic threats and environmental hazards[23]. Several news articles have highlighted the presence of illegal mining in the VMD[24–26] while a comparison of sand mining data from academic research shed some light on the magnitude of illegal mining in the VMD. One study[27] collated data from issued sand mining licenses in Vietnam to find that 28 Mm^3 of sand was extracted in 2015 from the VMD. Another study[19] used data collected by local government departments to show that 17.77 Mm^3/yr of sand was mined from the VMD in 2018. The most recent study[28] combined bathymetry surveys from a 100 km reach along the Tien River with a boat metrics driven mining intensity map retrieved from Sentinel-1 radar imageries to show that the sand mining budget of the VMD had increased from 37.8 Mm^3 in 2015 to 43.64 Mm^3 in 2018. The substantial difference between sand mining rates from government data[19,27] and independent research[28] in 2015 and 2018 suggests that the rate of illegal mining ranged from 10 Mm^3/yr in 2015 to 26 Mm^3/yr in 2018. Apart from these datapoints, the volume of sand illegally mined from individual provinces remains uncertain. In addition, while existing research have identified sand mining hotspots across the VMD[28–31], these studies were not able to identify where illegal mining was taking place.

In this paper, we quantify the extent of illegal riverbed mining in the VMD by comparing allowable limits of sand extraction set by the Vietnamese government with a systematically measured sand mining budget of the VMD by Gruel et al.[28]. Our work allowed us (1) to show locations where sand extraction potentially exceeded available sand supply, (2) to map out the extent of illegal mining in the VMD, and (3) to calculate the illegal sand mining budget for each province in the VMD. Given that existing research have focused on highlighting the reasons behind illegal sand mining, with the government data, we were able to present quantitative information on the amount of sand that was illegally mined and potentially unaccounted for. The quantitative insight from our work will provide baseline information on the scale of illegal sand mining in the VMD which will be useful for informing regulatory frameworks for sustainable sand mining.

Results

Depletion of officially stated sand reserves. Data on the allowable rates of sand extraction and the volume of sand reserve present were provided by the respective provincial governments[32–35] (Supplementary Tables S1–S11) and the information was used to assess the extent of sediment depletion along the length of the Tien and the Hau rivers in the VMD. The officially stated sand reserve (thereafter known as sand reserve) along the Tien River between Sa Dec and Vinh Long showed signs of being depleted. In addition, the sand reserve along the river near Tan Chau town in the north was also vulnerable to sediment depletion (Fig. 1a, b). Sediment depletion was determined by calculating the ratio of allowable sand extraction to the volume of sand reserve. A higher ratio meant that a greater proportion of the sand reserve was allowed to be extracted which suggest a higher likelihood of sediment depletion. In 2013, three mining licenses issued in Tien Giang province that allowed mining in the vicinity of Vinh Long city had a ratio of >0.90. Another four licenses issued in the same province had ratios >0.80 (Fig. 1a). In Dong Thap province, the sand mining licenses with the two highest ratios (0.82 and 0.95) permitted mining along the Tien River between Cao Lanh and Sa Dec cities (Fig. 1a). The license with the third highest ratio (0.66) allowed mining near Tan Chau town in the north (Fig. 1a). In 2018–2020, the licenses issued in Dong Thap that had the three highest ratios (0.81, 0.76 and 0.63) were for mining along the Tien River, slightly downstream from Tan Chau town (Fig. 1b).

Along the Hau River, potentially unsustainable sand mining had shifted downstream from around Long Xuyen city towards Can Tho city (i.e., southeast of Long Xuyen). In 2013, the two sand mining licenses issued in An Giang province that had the two highest ratios (0.57 and 0.55) authorized mining along the Hau River northwest of Long Xuyen city (Fig. 1a). In 2018–2020, the rate of sediment depletion was potentially higher in the section of the river between Long Xuyen and Can Tho cities. Notably, two sand mining licenses issued in Can Tho province had a ratio of 3 and one license had a ratio of 1 which meant that the total amount of sand that could be legally mined at these locations exceeded or equalled the volume of sand reserve (Fig. 1b). Overall, sediment depletion had worsened in Dong Thap province as the median ratio of total allowable extraction to the officially stated sand reserve had increased from 0.28 in 2013 to 0.48 in 2018–2020 (Fig. 1c).

Increase in allowable sand extraction. We used the total permitted area for sand extraction provided by the various provincial

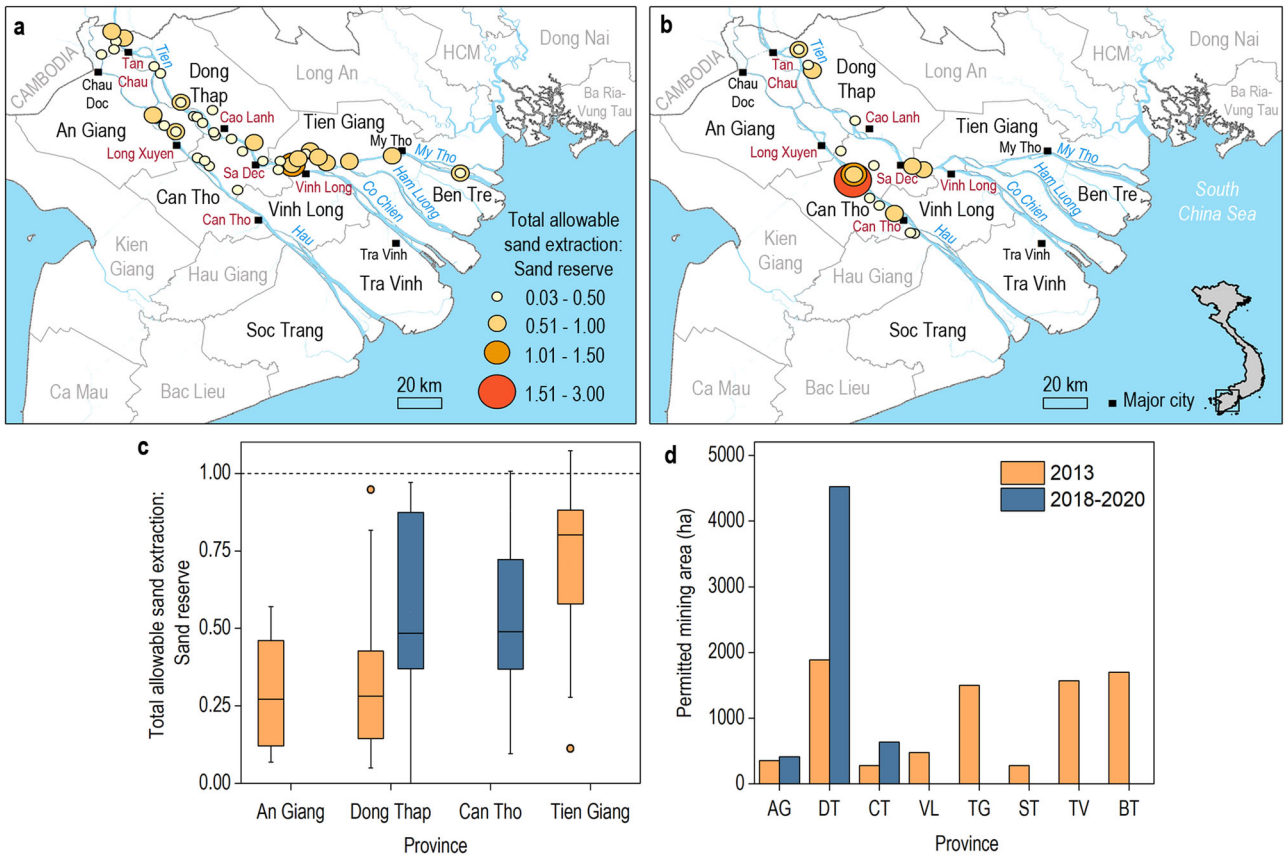

Fig. 1 Extent of sediment depletion in the VMD. a Ratio of total allowable sand extraction to volume of officially declared sand reserve for each mining license issued by the respective provincial governments in 2013**. b** Ratios for each sand mining license issued in 2018–2020. **c** Range of ratios for all the sand mining licenses issued in each VMD province in 2013 and 2018–2020. **d** Total permitted area of sand extraction for each province in the VMD. The abbreviations used are AG (An Giang), DT (Dong Thap), CT (Can Tho), VL (Vinh Long), TG (Tien Giang), ST (Soc Trang), TV (Tra Vinh) and BT (Ben Tre). The order of provinces on the x-axis reflects the location of provinces from upstream to downstream.

governments[32–35] (Supplementary Tables S1–S11) as a complementary dataset to confirm that sand mining was widespread in the VMD and a larger area was allowed to be mined in some provinces. In 2013, the total permitted area for sand mining followed the order: Dong Thap (1885 ha) > Ben Tre (1701 ha) > Tra Vinh (1571 ha) > Tien Giang (1499 ha) > Vinh Long (476 ha) > An Giang (354 ha) > Can Tho (278 ha) > Soc Trang (277 ha). Increases in permitted mining areas were observed in 2018–2020 for An Giang, Can Tho and Dong Thap. Notably, the total permitted sand mining area for Dong Thap increased 2.4 times to 4523 ha. Similarly, the sand mining area in Can Tho increased by 2.3 times from 278 ha to 634 ha while the permitted sand mining area in An Giang increased modestly by 58 ha (Fig. 1d).

An increase in the allowable rates of sand extraction accompanied the increase in the permitted mining area in An Giang, Dong Thap and Can Tho. To illustrate this, we provide a detailed breakdown of the allowable rate of sand extraction and the actual volume of sand extracted per year relative to the sand reserve present along the length of the Tien and Hau Rivers. The allowable rate of sand extraction and the volume of sand reserve present at each sand mining site were established by the respective provincial governments (Supplementary Tables S1–S11)[32–35] while the volume of sand extracted from the VMD was from Gruel et al.[28]. From where the Tien River started in Vietnam, the entire length of the river was divided into 21 ten kilometer reaches. At the 30–40 km and 60–70 km reach of the Tien River, the allowable rate of sand extraction in the 2018–2020 period was 3.5 to 4 times higher than the allowable rate of extraction in 2013. Meanwhile, the sand reserve at the 30–40 km reach had doubled from 11.55 Mm^3 in 2013 to 24.34 Mm^3 in 2018–2020. A doubling of the sand reserve from 11.27 Mm^3 to 22.89 Mm^3 was also noted at the 60–70 km reach (Fig. 2a, b).

The Hau River was divided into 22 ten kilometer reaches and at the 80–90 km reach near Long Xuyen city, the allowable rate of sand extraction increased 19-fold from 2013 to 2018–2020, from 0.22 Mm^3/yr to 4.20 Mm^3/yr. Unusually large increases in the allowable rates of extraction were also observed at the 100–110 km reach (9x increase from 0.20 Mm^3/yr to 1.83 Mm^3/yr) and at the 120–130 km reach (6x increase from 0.05 Mm^3/yr to 0.30 Mm^3/yr). In addition, the sand reserve doubled at the 100 to 110 km reach from 4.73 Mm^3 to 9.35 Mm^3 (Fig. 2c, d). Dramatic increases in allowable rates of sand extraction and the volume of sand reserve were unusual given that the sand replenishment rate along a river reach should not vary by a substantial amount inter-annually.

When the allowable rate of sand extraction for all the sand mining licenses issued in each province during the two study periods were totaled, the allowable rate of sand extraction increased from 11.5 Mm^3/yr in 2015 to 17.7 Mm^3/yr in 2018–2020. In 2013, the total allowable rate of sand extraction ranged from 1.4 Mm^3/yr in Vinh Long province to 9.5 Mm^3/yr in Dong Thap province. Allowable rates of sand extraction were only available for sand mining licenses issued in three provinces in 2018–2020. When totaled, the allowable rates ranged from 2.52 Mm^3/yr in Can Tho to 9.88 Mm^3/yr in Dong Thap.

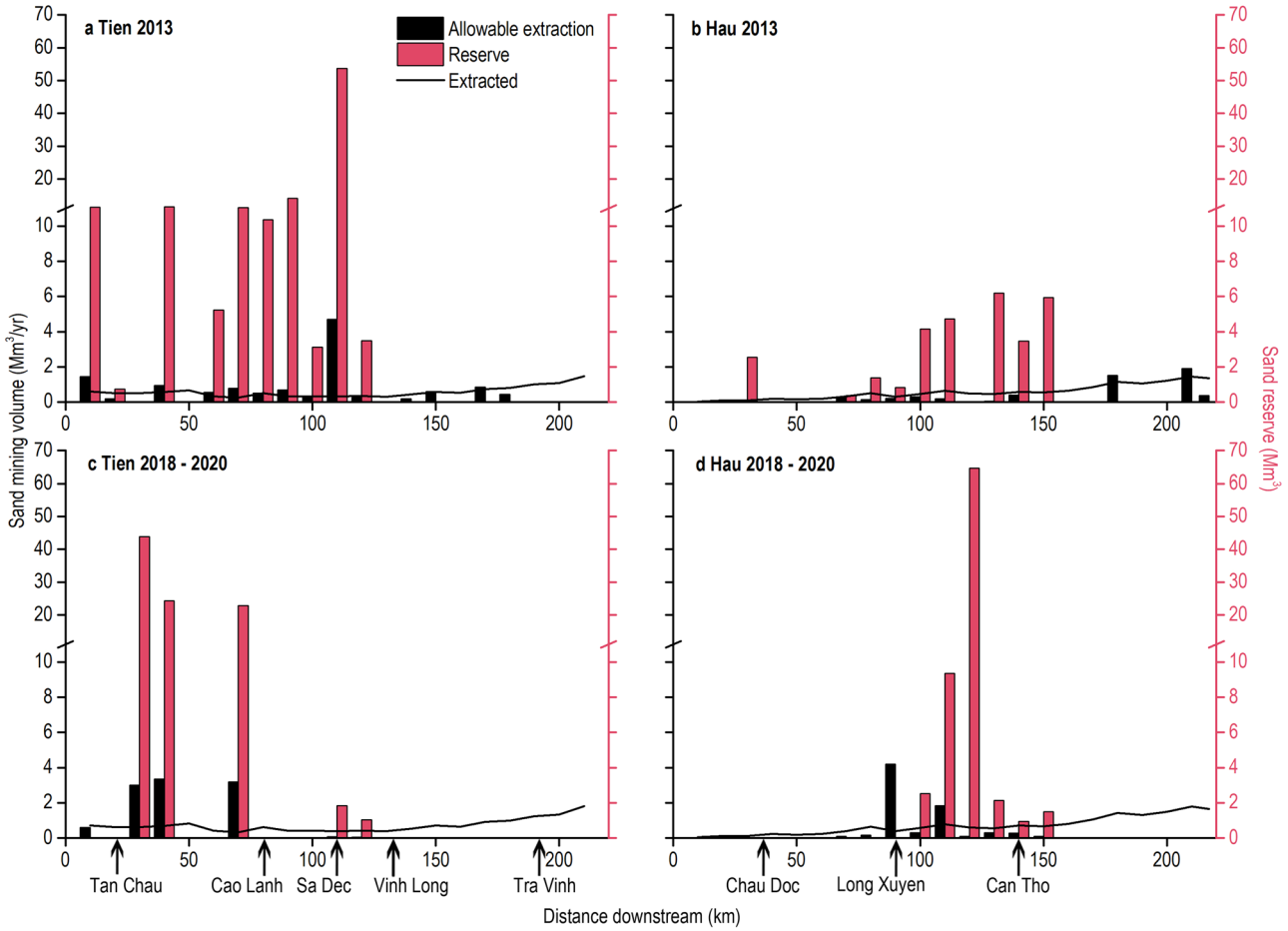

Fig. 2 The allowable rate of sand extraction and the actual volume of sand extracted relative to the officially declared sand reserve was presented longitudinally along the Tien and Hau Rivers. a Data for Tien River in 2013, **b** Data for Hau River in 2013, **c** Data for Tien River in 2018–2020, **d** Data for Hau River in 2018–2020. The entire length of each river was divided into 10 km reaches and the allowable rate of sand extraction, the actual volume of sand extracted and the volume of sand reserve present at each 10 km reach was shown. The 0 km mark was where the Tien and Hau Rivers start in Vietnam and the position of each 10 km reach relative to where the Tien and Hau River start in Vietnam was reflected on the x-axis. The locations of prominent towns and cities along the length of the Tien and Hau Rivers were also marked on the x-axis to allow easier identification of sand mining hotspots.

Table 1 Volume of illegally mined sand in the VMD.

	2013			2018–2020		
Province	**Volume of sand extracted (Mm^3/yr)**	**Allowable rate of sand extraction (Mm^3/yr)**	**Difference (Mm^3/yr)**	**Volume of sand extracted (Mm^3/yr)**	**Allowable rate of sand extraction (Mm^3/yr)**	**Difference (Mm^3/yr)**
An Giang	7.79	1.99	5.80	8.53	5.26	3.27
Dong Thap	18.45	9.50	8.95	21.85	9.88	11.97
Can Tho	3.00	NA	NA	2.78	2.52	0.26
Vinh Long	3.32	1.40	1.92	4.27	NA	NA
Tien Giang	2.23	3.38	−1.47	2.50	NA	NA
Soc Trang	0.44	3.79	−3.35	0.37	NA	NA
Tra Vinh	1.00	1.70	−0.70	1.10	NA	NA
Ben Tre	1.44	6.50	−5.06	1.50	NA	NA

The illegal mining rate was defined as the difference between actual volume of sand mined that was measured and the allowable rate of sand extraction set by the provincial government. A positive value indicated the presence of illegal mining as the volume of sand extracted in a given year exceeded the allowable rate of sand extraction per year. Conversely, a negative value meant that the volume of sand extracted was acceptable as the actual volume of sand extracted per year was less than the allowable rate of extraction per year. If the allowable rate of sand extraction was not available, the illegal mining rate was not calculated as it was not known if the allowable rate of sand extraction was zero or unlimited.

Although the allowable rate of sand extraction was the highest in Dong Thap, relative to the 2013 value, there was only a modest increase of 0.38 Mm^3/yr. The increase was the most pronounced in An Giang as the allowable rate had increased by 2.6 times from 1.99 Mm^3/yr in 2013 to 5.26 Mm^3/yr in 2018–2020 (Table 1).

Uncovering illegal sand mining. The illegal mining rate was defined as the difference between the actual volume of sand mined per year from Gruel et al.[28] and the allowable rate of sand extraction set by the respective provincial governments annually. The presence of illegal mining at specific locations along the

length of each river was first highlighted. In 2013, six out of 21 reaches along the Tien River had evidence of illegal sand mining (29%). Specifically, illegal mining was happening along the (1) 10–20 km reach near Tan Chau town, (2) 70–80 km reach near Cao Lanh city, (3) 90–100 km reach between Cao Lanh and Sa Dec cities, (4) 110–120 km between Sa Dec and Vinh Long cities, (5) 130–140 km reach near Vinh Long city and (6) 170–180 km reach near Tra Vinh city (Fig. 2a). The 170–180 km (illegal mining rate: 0.35 Mm^3/yr), 10–20 km (0.30 Mm^3/yr) and 130–140 km (0.23 Mm^3/yr) reaches had the highest rates of illegal mining, while the volume of illegally mined sand at the remaining four reaches were substantially lower (range: 0.01–0.09 Mm^3/yr). In short, illegal mining along the Tien River was the highest in the vicinity of Tan Chau town near the Cambodian border and around Tra Vinh city. In addition, illegal mining was also found along the length of the Tien River from Cao Lanh to Vinh Long with it being more severe from Sa Dec to Vinh Long.

In 2018–2020, three separate ten kilometer reaches along the Tien River were affected by illegal sand mining (14%). Illegal mining was happening along the (1) 0–10 km reach near Tan Chau town, (2) 100–110 km near Sa Dec city and (3) 110–120 km between Sa Dec and Vinh Long cities (Fig. 2b). Illegal mining along the 100–120 km reach along the river from Sa Dec to Vinh Long ranged from 0.32 to 0.37 Mm^3/yr, exceeding the illegal mining rate at the 0–10 km reach (0.13 Mm^3/yr) by more than two times. A comparison of illegal mining sites over the two time periods point to the persistence of illegal sand mining near the Cambodian border around Tan Chau town and further downstream between Sa Dec and Vinh Long cities. In addition, bed incision rates were higher around Tan Chau town, around Cao Lanh city and from Sa Dec to Vinh Long cities which coincided with where illegal sand mining was noted (Fig. 3a).

Along the Hau River, illegal mining was widespread from the area upstream of Long Xuyen city to Can Tho city. In 2013, illegal mining occurred in nine out of 22 ten kilometer reaches (41%) and the corresponding number for 2018–2020 was seven (32%). All but one reach was in the vicinity of or between Long Xuyen and Can Tho cities. (Fig. 2c, d). In 2013, the river reaches between 210–217 km (0.98 Mm^3/yr), 140–150 km (near Can Tho city; 0.56 Mm^3/yr) and 100–110 km (between Long Xuyen and Can Tho cities; 0.45 Mm^3/yr) had the highest rates of illegal mining. In 2018–2020, illegal mining continued along the river between Long Xuyen and Can Tho cities, as the reaches with the three highest rates of illegal sand extraction were between 140–150 km (near Can Tho city; 0.58 Mm^3/yr), 110–120 km (between Long Xuyen and Can Tho cities; 0.49 Mm^3/yr) and 70–80 km (near Long Xuyen city; 0.48 Mm^3/yr). Similarly, riverbed incision was more severe along the river around Long Xuyen city and towards Can Tho city (Fig. 3a).

A total of 16.67 Mm^3/yr of sand was illegally mined from the riverbed in An Giang, Dong Thap and Vinh Long provinces in 2013. In that year, the amount of illegally mined sand was the highest in Dong Thap (8.95 Mm^3/yr), followed by An Giang (5.80 Mm^3/yr) and Vinh Long (1.92 Mm^3/yr) (Table 1, Fig. 3b, d). Though data for 2018–2020 was limited, the amount of sand illegally mined from An Giang, Can Tho and Dong Thap combined was 15.5 Mm^3/yr or 93% of the 2013 figure. In 2018–2020, Dong Thap continued to be a illegal sand mining hotspot as the volume of illegally mined sand had increased from 8.95 Mm^3/yr in 2013 to 11.97 Mm^3/yr in 2018–2020 (34% increase). Conversely, the volume of sand mined illegally in An Giang decreased by 2.53 Mm^3/yr (Table 1, Fig. 3c, d). Based on the amount of sand that was illegally extracted, illegal mining was concentrated in An Giang and Dong Thap province. Meanwhile, a smaller volume of sand was illegally mined in Can Tho and Vinh Long. The Vietnamese government was aware of illegal sand mining in the VMD as the government reported that illegal mining was taking place in An Giang, Can Tho, Dong Thap and Tien Giang provinces[35]. Our findings agreed with the Vietnamese government data as we also acknowledged the presence of illegal mining in An Giang, Dong Thap and Can Tho. In addition, the areas with illegal mining in our study were in the in the vicinity of the illegal mining spots identified by the Vietnamese authorities (Fig. 3a, Table 2).

The presence of illegal mining in the VMD was confirmed by plotting the locations of all sand mining barges with crane (BC) that were found along a stretch of the Hau River from 2018-2022. We mapped BCs because they were used to extract sand from the riverbed[28]. The locations of the BCs were overlaid on a map that specified where sand mining was allowed along the Hau River in Can Tho province. On the map we created, we observed that while sand mining largely happened outside restricted mining areas (pink areas), it did not always occur in approved mining areas (yellow areas). Instead, active BCs were often detected in areas currently under investigation for future mining (blue areas) or in "gray areas" where mining was neither permitted nor restricted (Fig. 4). We considered mining outside the permitted areas to be "illegal," and although we only provide a snapshot of illegal mining for a limited section of the Hau River, we hypothesized that sand mining outside permitted mining areas was likely to be common across the VMD as our results revealed illegal mining in multiple locations across the VMD.

Discussion

The riverbed around areas affected by illegal sand mining had a higher rate of incision which contributed to a drawing down of the officially stated sand reserves as a higher than permitted volume of sand was removed. Along the Tien River, the area from Sa Dec to Vinh Long city was an illegal sand mining hotspot with high rates of riverbed incision that contributed to sediment depletion. Up north, the riverbed near the Cambodia-Vietnam border was deeply incised as excessive mining was happening in the vicinity of Tan Chau city. Illegal sand extraction was rampant along the Hau River from Long Xuyen to Can Tho cities and sand supplies there may be irreparably exhausted. The hotspots of illegal mining that we found in our study also happened to be along sections of the river with high riverine traffic. Based on PlanetScope imagery from 2018 to 2021, the length of the river near the Cambodia-Vietnam border on the Tien River, around Sa Dec and near Long Xuyen had a higher than usual concentration of vessels[18]. At the provincial level, our results showed that illegal mining was ongoing in An Giang, Can Tho, Dong Thap and Vinh Long provinces which agreed with the results from Jordan et al.[19]. In that study, dredging was found to be concentrated in the same four provinces.

The amount of illegally mined sand decreased from 16.7 Mm^3/yr in 2013 to 15.5 Mm^3/yr in 2018–2020. Although the volume of sand extracted from the VMD had increased progressively from 37.80 Mm^3/yr in 2015 to 45.40 Mm^3/yr in 2018–2020 (ref. [28]), an increase in the allowable rate of sand extraction from 11.5 to 15.1 Mm^3/yr in An Giang and Dong Thap contributed to a decrease in the rate of illegal mining. This was because the illegal mining rate was defined as the difference between actual volume of sand mined and allowable rate of sand extraction set by the provincial authorities. An increase in the permitted mining area by 1.2 to 2.4 times in An Giang, Can Tho and Dong Thap in 2018–2020 allowed more sand to be legally extracted to meet demand. The allowable rates of sand extraction and the volume of sand reserve provided by the provincial governments may have been arbitrarily determined as the deputy head of the Southern Institute of Water Resources Research (SIWRR) said that the

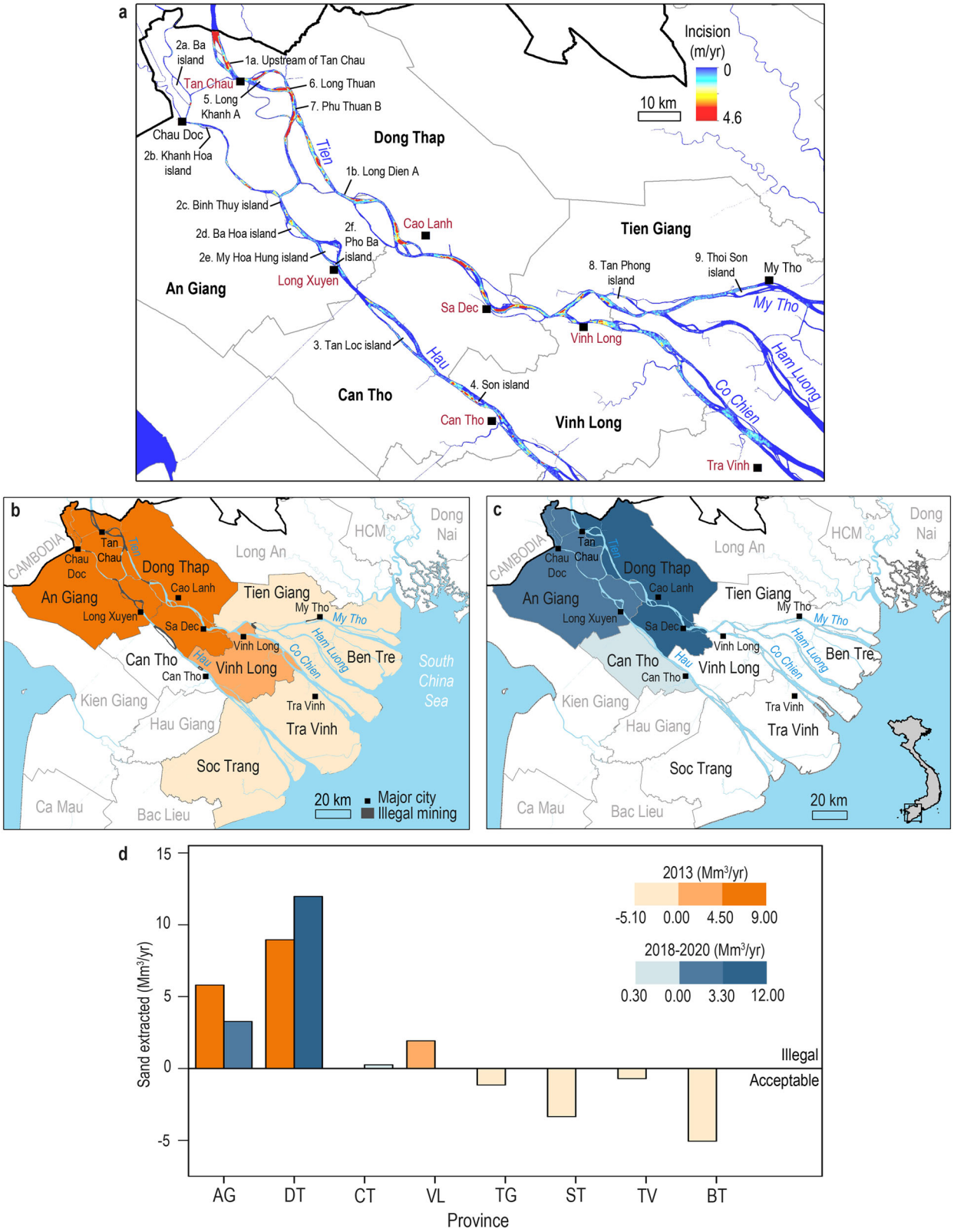

Fig. 3 Distribution of illegal sand mining in the VMD. a Map of illegal sand mining sites identified by the Vietnamese government and the average riverbed incision rates in the VMD between 2015–2020. **b** Overview of illegal sand extraction across the VMD in 2013 and **c** 2018–2020. The channel area around the illegal sand mining sites reported by the government in 2013 were shaded in **b**. **d** Volume of sand extracted across the VMD in 2013 and 2018–2020. The illegal mining rate was not available for Can Tho in 2013 as sand mining licenses issued by the Can Tho provincial government did not have data on the allowable rates of sand extraction. The abbreviations used are AG (An Giang), DT (Dong Thap), CT (Can Tho), VL (Vinh Long), TG (Tien Giang), ST (Soc Trang), TV (Tra Vinh) and BT (Ben Tre). The order of provinces on the x-axis reflects the location of provinces from upstream to downstream.

Table 2 Locations with illegal sand mining.

Province	Illegal mining hotspots
An Giang	1. On the Tien River, (a) in the upstream area of Tan Chau town, (b) in the area around Long Dien A commune, Choi Moi district.
	2. On the Hau River, from Chau Doc to Long Xuyen, specifically (a) Ba island, (b) Khanh Hoa island, (c) Binh Thuy island, (d) Ba Hoa island, (e) My Hoa Hung island and (f) Pho Ba island.
Can Tho	3. Tan Loc island.
	4. Son island.
Dong Thap	5. Long Khanh A commune, Hong Ngu district.
	6. Long Thuan, Hong Ngu district.
	7. Phu Thuan B commune, Hong Ngu district.
Tien Giang	8. Area at the beginning of Tan Phong island.
	9. Area near Rach Mieu bridge on the north bank of Thoi Son island

The information was provided by SIWRR[35].

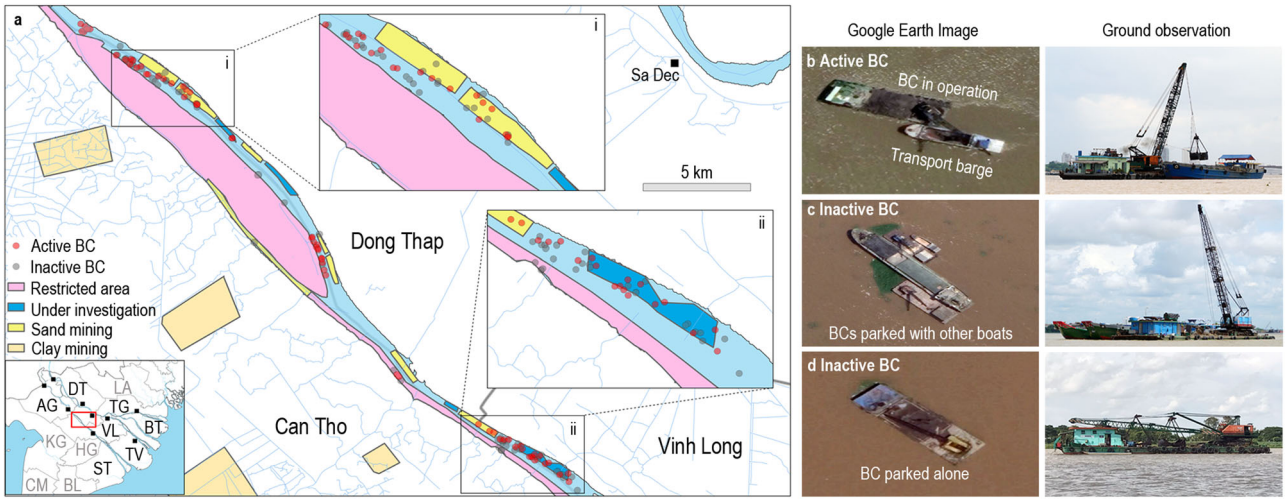

Fig. 4 Evidence of illegal sand mining. a Where sand mining was allowed and not allowed along a stretch of the Hau River. "Restricted area" and "Under investigation" refers to areas where sand mining was not allowed and therefore, mining in these places was considered to be "illegal". On the other hand, "Sand mining" refers to areas approved for sand mining. The locations of all the barges with crane (BC) that were found along the same stretch of the river from 2018-2022 were mapped and overlaid on the main map. We used Google Earth Pro to plot the locations of all the BCs as BCs were used to extract sand from the riverbed. Simultaneously, we identified whether the barge was active or inactive. **b** An active BC was paired with a transport barge that collected the mined sand. An inactive BC referred to a BC that was either **c** parked together with other boats or **d** parked alone. By mapping the active and inactive BCs and overlaying the information on a map with where sand mining was allowed and not allowed, we were able to confirm the presence of illegal mining in a small part of the VMD. Map data for Google Earth Image: Google, © 2023 Maxar Technologies. Photo credit for ground observation: first author.

sand supply in the VMD has never been calculated as provincial officials did not have the technical and financial capacity to do so[36]. As such, the volume of sand that was legally allowed to be mined may not reflect the existing supply of sand and with excessive sand mining, how much sand remains on the riverbed remains uncertain.

Even though we had defined illegal mining as exceeding the allowable mining rates, illegal mining is a broad term that includes mining outside the approved sand mining areas, mining without a valid license, the use of unregistered sand mining boats and mining at night. Specifically, sand mining is prohibited between 1800 h – 0600 h in Vietnam[35]. The practice of mining outside approved sand mining areas and extracting more sand than permitted was confirmed by Le et al.[25] who wrote that it was necessary to "mine beyond the mine otherwise there is not enough sand." Mining outside approved mining areas (Fig. 4) was to ensure that there is still sand left at sites where sand mining was permitted so that existing mining licenses will be extended by the authorities[25]. The Vietnamese government acknowledged that non-compliance with mining regulations was problematic and like other countries with illegal sand mining, inadequate resources and monitoring meant that the problem of illegal mining could not be fully solved[35]. In addition, each provincial government only had jurisdiction over mining activities within their provincial boundaries and there was limited inter-provincial cooperation amongst neighboring provinces with shared provincial boundaries[35]. The lack of cooperation was evident as each province had issued separate documents to regulate sand mining within their provincial boundaries[32–34]. Another loophole that allowed sand mining operators to get away with illegal mining was the use of fake invoices to legitimize the illegally mined sand. On the invoices, the volume of sand that was mined was under-reported and the under-reporting allowed the sand mining operators to evade taxes as well[25]. Ultimately, it is difficult to determine if the sand was illicitly sourced once it leaves the extraction point[37] and the loopholes have allowed illegal mining to flourish.

Illegal mining continues to be a problem in the VMD up to this day even though our study period was up to 2020. In August 2023, the Vietnamese police had announced that a large illegal mining ring was busted in An Giang province. Officials from the Department of Natural Resources and Environment of An Giang province and directors of the Trung Hậu Investment Joint Stock

Company were arrested for extracting more than 4.7 Mm^3 of sand from the Tien River as the amount of sand the company had extracted was three times more than the authorized limit of 1.5 Mm^3 (ref. [38]). As a result of the crackdown and the subsequent reduction of sand supply, sand prices increased by VND 60,000 to 70,000 (US$2.50 to 3.00) to VND320,000 to 330,000 (US$13 to 14) per cubic meter. With two major construction projects in the VMD (ie. 110 km Can Tho-Ca Mau Expressway and 188 km Chau Doc-Can Tho-Soc Trang Expressway)[39,40], the clamp down on illegal mining may just be a temporary thing. To deal with illegal mining, the authorities have mandated the installation of security cameras on dredging rigs and the data collected from the cameras must be transmitted to the provincial authorities[41]. It is uncertain if such a plan is feasible but measures to gather real-time data on sand mining activities may provide useful data for informing regulatory frameworks.

The limited management of sand mining activities is exacerbated by the effect upstream dams have on sediment supply in the Mekong[42,43] as (il)licit sand mining in the VMD further contribute to the sediment deficit[19]. Excessive sediment removal has caused the water in the river channel to become sediment starved and this "hungry water" has increased riverbank erosion and induced bank collapse[44,45]. Multiple instances of bank erosion and bank collapse were identified near sites of lowered and irregular riverbeds[31] and a news article[46] reported that between 2018 and 2020, 1808 houses in the Mekong Delta collapsed into the river due to erosion. In addition, farmlands, fishponds and shops were also lost when banks collapse[47]. Widespread bank erosion and collapse in the VMD have caused residents living along the riverbank to live in fear and anxiety as their land and properties may be next[48,49]. Decreased river sediment supply has also contributed to coastal erosion. Analysis of Landsat satellite images from 1973 to 2015 showed that 66% of the VMD shoreline showed signs of erosion and the VMD had lost 10.8 km^2 of land from 2005 to 2015 (ref. [50]). Another study[51] used SPOT 5 images from 2003 to 2012 to show that 90% of the 180 km long coastline was in the retreat with some parts receding by up to 50 m/yr. The cumulative land loss from coastal erosion mean that the 23–90% of the delta is at risk of being underwater by 2100 (ref. [52]).

Riverbed sand mining also lowers the riverbed resulting in lowered water levels in the river channel and decreased hydrological connectivity as the river water level has to be at least 0.07 m to be hydrologically connected to the irrigation canals. This decrease translates to a decrease in available water for irrigation, increased cost of pumping water for irrigation, and reduced floodplain flooding[7,53]. In addition, sand mining was also identified as one of the factors driving the intensification of salinity intrusion in recent years. Increased soil salinity is problematic as it renders the land unsuitable for cultivating major cash crops such as rice[8,27,54,55]. Although the ecological impacts of sand mining in the VMD is not well studied, many studies from elsewhere have pointed out that sand mining destroy spawning grounds, interfere with migratory routes and cause a decline in local fish populations as habitats are destroyed and turbidity increase[9,56,57]. The ecological impacts of sand mining is likely to be serious in the VMD as one report[58] mentioned that the fish catch fell by 50% when sand dredging started in Koh Kong province in Cambodia. Besides fish, amphibians, birds and mammals living in the VMD are also affected as they are also dependent on the Mekong River for food and shelter[59]. Sand is a critical resource for fulfilling socio-economic development and the high demand for it has unfortunately contributed to the heavy environmental toll.

Concluding remarks. A systematic and unified approach to manage sand mining in the VMD is needed and our work highlights the need to possibly reset the allowable rates of sand extraction, update the quantity of sand reserve and re-evaluate where sand can be mined. Demand for sand in Vietnam is likely to remain high as the country develops rapidly, and it is impractical to stop sand mining completely. Local resource users also prefer more localized measures that are compatible with business as usual[60], so enforcement action to halt and punish illegal mining is unlikely to stop it. As such, rigorous scientific research should be conducted to identify fluvial reaches where sustainable sand extraction can be carried out. By determining locations where river sand replenishment rates are high enough to meet demand and designating these as sites for sustainable sand extraction, researchers can help policymakers minimize environmental degradation without jeopardizing the livelihoods of sand miners.

Data and methods

The Mekong Delta is one of the largest delta in the Asia at 93,781 km^2 and it is located at the mouth of the Mekong River[61–63]. The delta spans the triangular strip of land between Phnom Penh in Cambodia, the mouth of the Saigon River to the east and the southwestern cape of the Ca Mau Peninsula to the west[62]. Our study focused on Vietnamese Mekong Delta (VMD) or the part of the Mekong delta within the Vietnamese border. 35,158 km^2 of the Mekong Delta lies within Vietnam with another 23,346 km^2 in in Cambodia[63]. The Tien (Mekong) and the Hau (Bassac) Rivers are the two major distributaries of the Mekong River that flow through Vietnam to the South China. The Hau River is linked to the Tien River through the Vam Nao Channel[30,62]. Barges with crane (BC) are commonly used to scoop sand from the riverbed while suction pumps are sometimes used to pump sand from the riverbed[35].

The extent of sediment depletion and illegal mining in the VMD was revealed using a mixed method approach, combining remotely sensed observations, field-based measurements, and government statistics provided by the various provincial governments of Vietnam[32–35]. The actual sand mining budget was derived from bathymetry surveys and boat density data by Gruel et al.[28]. We then compared the sand mining budget from Gruel et al.[28] with official records from the Vietnamese government.

Provincial government data. We obtained a 2013 government report published by the Southern Institute of Water Resources (SIWRR)[35]. The report compiled information from various provincial governments in the VMD and contained information such as the number of sand mining licenses granted for eight provinces in the VMD - An Giang, Ben Tre, Can Tho, Dong Thap, Soc Trang, Tra Vinh, Tien Giang and Vinh Long (Supplementary Tables S1–S8). For each sand mining license, details like the name of the river to be mined, commune and district names of sand mining locations, size of mining area (ha), the number of year(s) the license was valid for, size of the officially declared sand reserve (Mm^3) and the allowable rate of sand extraction (Mm^3/yr) were extracted (Table 3).

To evaluate the extent of sediment depletion and illegal sand mining after 2013, we obtained three provincial government reports that had information on the number of sand mining licenses issued in An Giang[32], Can Tho[33] and Dong Thap[34] (Supplementary Tables S9–S11). The data for An Giang was published by the An Giang Provincial People's Committee (AGPPC), the data for Can Tho was published by the Can Tho Provincial People's Committee (CTPPC) and the data for Dong Thap was from the Dong Thap Provincial People's Committee (DTPPC). In terms of data availability, the data for An Giang was for 2019–2021; the data for Can Tho was from 2018 to 2020 and

Table 3 The number of sand mining licenses issued for each province in the VMD and the number of licenses with complete information for each mining parameter.

			Number of licenses for each sand mining parameter:					
Time period	Province	Number of licenses	River	Sand mining location	Mining area (ha)	License validity	Sand reserve (Mm^3)	Allowable capacity (Mm^3/yr)
2013	An Giang	14 (10)	14	14	14	14	13	14
2013	Ben Tre	16	9	16	0	13	0	16
2013	Can Tho	7 (6)	0	7	7	0	7	0
2013	Dong Thap	22	19	22	22	20	22	20
2013	Soc Trang	4	0	4	4	4	0	4
2013	Tra Vinh	34 (17)	0	0	34	0	34	34
2013	Tien Giang	31 (19)	0	31	31	18	27	18
2013	Vinh Long	9	0	9	9	9	0	9
2019–2021	An Giang	11 (8)	11	11	11	11	0	11
2018–2020	Can Tho	13	0	13	13	0	13	13
2015–2020	Dong Thap	22	22	22	18	0	18	18

Some sand mining licenses contained sub-licenses that permitted mining in multiple locations. Sub-licenses were considered as a single license to simplify data analysis. The number in parentheses for the "Number of licenses" refers to the actual number of licenses granted by the various Vietnamese provincial governments where the sub-licenses were not counted separately.

for Dong Thap, the data was from 2015 to 2020. Like the 2013 report, the name of the river to be mined, commune and district names of sand mining locations, size of mining area (ha), the number of year(s) the license was valid for, size of sand reserve (Mm^3) and the allowable rate of sand extraction (Mm^3/yr) were included in the provincial government reports (Table 3).

As the focus of our work was on illegal riverbed mining, the provinces we included in our study were along the Mekong River where riverbed sand mining was taking place. Hau Giang was excluded from our analysis as no data was available even though the province was next to the Mekong River. The absence of data was because there was very little sand mining in the province[35].

Volume of sand extracted. In this study, primary data from Gruel et al.[28] was used to calculate the volume of sand extracted from each 10 km reach along the Tien and Hau Rivers. The two rivers were chosen as they are the two major distributaries of the Mekong River[64] (Co Chien River was included as part of the Tien River). In the study by Gruel et al.[28], a bathymetry survey along a 100 km stretch of the Tien River was first carried out with a Teledyne RD Instrument Workhorse Rio Grande 600 KHz Acoustic Doppler Current Profiler (ADCP). 491 cross sections were surveyed in July 2014 and another 380 cross sections were surveyed in September 2018. The starting point of the survey was 15 km downstream of the Vietnam-Cambodia border and the survey ended 12 km downstream of My Thuan bridge. A bathymetry difference map (40 m resolution) was generated to show accumulation and incision between 2014 and 2017.

A boat classification system was then developed with high resolution Google Earth imagery (0.5 m resolution) from 2019 to 2020. A total of 1,150 boats along a 130 km reach of the Tien River and part of the Co Chien branch were documented. To validate the boat classification system, an onsite survey was conducted along an 80 km reach of the Tien River over three days (22 December 2020, 3 and 15 January 2021). Sand mining hotspots were visited at 5.45 am and 6.11 pm to coincide with the passing of the Sentinel 1A satellite. GPS coordinates of the boats were recorded, and photos of individual boats were taken to allow us to identify barges with crane (BC) and other sand mining boats. Such boats were typically ≥70 m.

The river channels were delineated with Normalized Difference Water Index (NDWI) from Landsat 8 Operational Land Imager (OLI) imagery. To derive a VMD study area channel mask, the area within 50 m of the river channel was cropped out to minimize noise from non-active boats and non-sand mining activities along the river edge. In addition, a 100 km study area channel mask where the bathymetry survey was conducted was also produced (Tien section delineation).

Next, 293 Sentinel-1 radar images (20 m resolution) from October 2014 to December 2020 were used to derive a boat density map (number of boats per km^2). The images were pre-processed with radiometric, geometric calibration, removal thermal noise and georeferenced with WGS84. A 0.5 threshold was applied to the scattering coefficient in each image to remove pixel artefacts. The selected pixel clusters were converted into a binary raster and cropped with the VMD study area channel mask. Using each ≥70 m boat as a point, a 10 m resolution boat density map was created for all the Sentinel-1 images collected from October 2014 to December 2017. A 200 m radius buffer was created around the center of each boat. A length of ≥70 m was chosen as fieldwork carried out in 2020 and 2021 showed that barges with crane (BC) that were commonly used to mine sand from the riverbed were often of that length.

All the boat density maps were put together to form a heat map that showed the locations of all the boats and the raster values were normalized by dividing by 91 (the total number of images from 2014-2017) to obtain a density of boat per km^2 per day. The same 100 km section of the Tien River where the bathymetry survey was conducted (Tien section delineation) was cropped out from the heat map and the map was resampled from 10 m to 40 m to match the resolution of the bathymetry difference map. The raster values were overlaid with the bathymetry difference raster (61,663 pixels in total). 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 then derived to estimate the riverbed incision rate based on daily boat density.

The boat density map for the entire VMD were grouped into three-year intervals (ie. 2015–2017, 2016–2018, 2017–2019, 2018–2020). The regression equation that was derived earlier was applied to these four time periods to generate an incision map for each three-year period. The incision map was resampled to 20 m. All the raster values for each three-year set were divided by three to estimate incision rates/yr. The volume of sand extracted/yr was derived from the incision rate/yr and channel area. Overlapping values for each year were averaged to attain an average value for each year.

Table 4 Average rates of incision in the Tien and Hau Rivers from 2015 to 2020.

Year	Average incision (m)
2015	0.046
2016	0.048
2017	0.057
2018	0.053
2019	0.056
2020	0.061

The incision data was from Gruel et al.[28].

To calculate the volume of sand extracted from each 10 km reach along the Tien and Hau Rivers, from where the Tien and the Hau rivers begin on the Cambodian-Vietnam border, each river was first divided into 10 km sections (reach) on ArcMap 10.8.1. The area of each 10 km reach was then calculated on the same ArcMap software. The average incision rate for the Tien and Hau Rivers from Gruel et al.[28] (Table 4) was multiplied by the area of each 10 km reach to determine the volume of sand extracted in each 10 km reach in a given year. The volume of sand extracted from each 10 km reach along the Tien and Hau Rivers was calculated for the years 2015, 2018, 2019 and 2020. The 2018, 2019 and 2020 volumes were averaged and referred to as data from 2018 to 2020.

Data comparison. The 2013 government data[35] (Supplementary Tables S1–S8) was compared to the actual volume of sand extracted in 2015 that was calculated by Gruel et al.[28]. We compared government data from 2013 with 2015 sand extraction data as the total volume of sand extracted every year in 2015, 2016 and 2017 differed by only 1 Mm^3/yr. The small difference made it valid to make temporally inconsistent comparison as we were not able to obtain sand mining data for the same year. Provincial government data for An Giang[32] (2019–2020; Supplementary Table S9) Can Tho[33] (2018–2020; Supplementary table S10) and Dong Thap[34] (2015–2020; Supplementary Table S11) were compared to the average volume of sand extracted from the years 2018–2020. The 2018-2020 sand mining data was also from Gruel et al.[28]. The years 2018–2020 was chosen because it overlapped with the data availability for these three provinces. Calculating the volume of sand extraction for the specific years in which government data was available was considered but not implemented because it was challenging to present temporally inconsistent data. For brevity, we refer to the two study periods as 2013 and 2018–2020 to facilitate the comparison of sand mining rates over the two time periods. Our priority was to show if there was an upward or downward trend in illegal mining over two temporal scales and our method can be considered scientifically valid and practical in our circumstances.

Sustainability of sand resources. We calculated the ratio of total allowable sand extraction (Mm^3) to the volume of officially stated sand reserve (Mm^3) to estimate the extent of sediment depletion over time and space. The data used to calculate this ratio were from the various provincial governments[32–35]. Firstly, the total allowable sand extraction (Mm^3) was determined by multiplying the allowable rate of sand extraction/year (Mm^3/yr) by the number of years the issued sand mining license was valid for.

For Dong Thap, the total allowable sand mining capacity (Mm^3) for 2015 and 2016–2020 were summed up and divided by the volume of sand reserve (Mm^3) to obtain the overall ratio for 2015–2020. Next, mining licenses issued in Ben Tre (Supplementary Table S2) and Tien Giang (Supplementary Table S7) in 2013 had no information on the validity period of each license. Therefore, we indirectly derived the number of years the license was valid for from the serial number of each license. To do so, we assumed the year on the serial number was the year in which the license was issued, and we determined the license validity from the difference between the date or year listed under the column "Term of exploitation" and the year on the serial number. For simplicity, we counted full years and did not include periods less than a year (Eg. License start date: 15 June 2006, license end date: 30 Nov 2013. License validity was counted as 7 years). If the year was not reflected in the serial number, we then assumed that the license was valid for one year. Lastly, the licenses issued in Can Tho for 2018–2020 were considered to be valid for three years as the government document issued in 2018 outlined the use of sand until the year 2020.

A spatial overview of the ratio for each mining license issued in 2013 was presented in Fig. 1a. The ratio for each 2018–2020 mining license was presented in Fig. 1b. Some mining licenses permitted sand mining in more than one location and the larger location that was allocated was used to map the location of the given license.

Boxplots were also used to give a general overview of the range of ratios for all the licenses issued in a particular province over the two time periods (Fig. 1c). A ratio of 1 means that the total amount of sand that was allowed to be mined was equal to the amount of sand reserve. A ratio of >1 means that the amount of sand allowed to be extracted was higher than the sand reserve and sand mining was possibly depleting the sand reserve. Conversely, a ratio <1 means that the volume of sand extracted was less than the amount of sand reserve. Values closer to 1 suggest that the sand reserve present had a higher possibility of becoming exhausted in the future if sand mining continues unabated. The order of provinces in Fig. 1c reflects the location of provinces from upstream to downstream.

Although there was no background information on how the allowable rates of sand extraction or volume of sand reserve present were derived and we did not know if these values were derived from rigorous scientific investigation, we assessed the spatial extent of sediment depletion based on the information available. Arguably, our method for determining sediment depletion was not perfect but the data provided us with an opportunity to determine the extent of sediment depletion in the VMD. Presently, most research on sand mining had focused on determining the volume of sand extracted and there is no baseline information on the amount of sand reserve present. Information on the limits of sand extraction set by the government was also not available. As such, knowing the allowable rates of sand extraction was valuable as it provided us with a threshold to determine if the volume of sand was legally or illegally mined.

Permitted sand mining area. We present an overview of the total permitted sand mining area for each province in the VMD in 2013 and 2018–2020 to highlight the spatial and temporal variations over two distinct time periods (Fig. 1d). The permitted sand mining area for each province was the sum of all the mining areas for each mining license issued in the province. We used this data to show that sand mining was widespread in the VMD as data on allowable rates of sand extraction and the amount of sand reserve present was sometimes incomplete (Table 3).

Allowable rates of sand extraction and total volume of sand reserve. To calculate the allowable rates of sand extraction and the total volume of sand reserve along each 10 km reach of the Tien and Hau rivers, individual values associated with each sand mining license in each specific reach were summed up to give a

representative value for each 10 km reach. These values were compared to the volume of sand extracted (Mm^3/yr) from each 10 km reach (Fig. 2). We also amalgamated all the allowable rates of sand extraction for all the sand mining licenses issued in each province during the two study periods to obtain the volume of sand that was permitted to be mined in each province (Table 1). We then used this value to determine the rate of illegal mining at the provincial scale.

Evidence of illegal mining from the Vietnamese government. We took a map of riverbed incision rates from 2015 to 2020 by Gruel et al.[28] to show where the riverbed was incised. The locations of illegal mining sites listed by the Vietnamese government in the 2013 report[35] were plotted on this incision rate map to determine if sites with high riverbed incision were concurrently sites of illegal mining (Fig. 3a). A comparison between inconsistent years (ie. 2013 vs 2015–2020) was made as the incision rate data we had was an average over six years which allowed us to show the temporal variability in incision rates relative to the sites of illegal mining that was furnished in the 2013 SIWRR report[35].

Determining the rate of illegal mining. The rate of illegal sand extraction was defined as the difference between the actual volume of sand mined per year (Mm^3/yr) and the allowable rates of sand extraction set by the provincial authorities every year (Mm^3/yr). The actual volume of sand mined per year was obtained from Gruel et al.[28] while the allowable rates of sand extraction for each province were from the SWIRR[35] and the various the various provincial governments[32–34]. A positive value indicated the presence of illegal mining as the volume of sand extracted exceeded the allowable rate of sand extraction per year. Conversely, a negative value meant that the volume of sand extracted was acceptable as the actual volume of sand extracted per year was less than the allowable rate of extraction per year. The negative value also referred to the amount of sand that had to be mined before the allowable limit was reached.

The volume of sand that was illegally mined in each 10 km reach along the Tien and the Hau Rivers was calculated. If the allowable rate of sand extraction was not available at a given reach, the illegal mining rate was not calculated as it was not known if the allowable rate of sand extraction was zero or unlimited. We mapped the spatial distribution of illegal sand mining across all the VMD provinces in 2013 (Fig. 3b) and 2018–2020 (Fig. 3c). In addition, we calculated the volume of sand that was illegally mined in each province in 2013 and 2018–2020 (Fig. 3d). For convenience, the volume of illegally mined sand in each province in the VMD was presented in Table 1 together with provincial level values on the allowable rates of sand extraction and the volume of sand extracted. Can Tho province did not have published data on the allowable rates of sand extraction and illegal sand mining rate was not calculated (Supplementary Table S3).

Even though the government data did not have methodological information on how allowable rates of sand extraction and quantity of sand reserve was determined, the government data was valuable as it gave us the first opportunity to validate the level of illegal mining in a key sand mining hotspot. While it was possible to determine the actual volume of sand extraction and the amount of sediment replenishment via scientific means, without information on what amount of sand extraction was legally acceptable by the government, it was impossible otherwise to determine the amount of sand that was illegally extracted.

Mapping illegal mining. A map on the "Planning, exploitation and use of mineral resources in Can Tho City projected to 2020 and a vision to 2030" (ref. [33]) was digitized on ArcMap 10.8.1 and used as a base map to highlight the presence of illegal mining in the VMD (Fig. 4a). The base map contained information on (1) restricted areas for mining activities, (2) locations where sand mining licenses were extended, (3) locations where new mining licenses were issued, (4) sites where sand mining was ongoing and (5) areas currently under investigation for future mining. The locations of (6) inland clay mines and (7) inland brick clay mines were also found on the map and digitized accordingly. (1) and (5) were considered areas where sand mining was currently not permitted. Conversely, we grouped (2), (3) and (4) into a category called "Sand mining," to show that these were permitted sand mining areas. Lastly, (6) and (7) were amalgamated into a category called "Clay mining."

We then used Google Earth Pro to map the locations of all the barges with crane (BC) that were found along the same stretch of the river from 2018 to 2022. The images from Google Earth Pro were provided by Maxar Technologies and the resolution was high enough to discern the type of boats present. We mapped BCs because they were used to extract sand from the riverbed[28]. When we mapped the location of each BC, we also noted if the barges were active or inactive. An Active BC was paired with a transport barge that collected the mined sand (Fig. 4b). An inactive BC referred to a BC that was either parked together with other boats (Fig. 4c) or parked alone (Fig. 4d). We then overlaid the locations of all the active and inactive BCs we mapped over the base map to show the distribution of BCs along the river. In particular, the map we created allowed us to show that sand mining did not always occur in allowable mining areas. An overview of the BC data we collected from Google Earth is provided in Supplementary Table S12.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files. The data used for generating the charts are available at: https://researchdata.ntu.edu.sg/dataset.xhtml?persistentId=doi:10.21979/N9/WFT9MM.

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Author contributions

K.W.Y.: Formal analysis, Writing - Original draft & Editing, Visualization. E.P.: Conceptualization, supervision, funding acquisition, Writing - Review & Editing. D.D.T.: Data acquisition, Writing - Review & Editing. H.H.L.: Data acquisition, Writing - Review & Editing. L.F., J.W., A.D.S.: Funding acquisition, Writing - Review & Editing. C.R.G.: Writing - Review & Editing.

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Correspondence and requests for materials should be addressed to Edward Park.

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