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Intensified susceptibility to riverbed incisions under sand mining impacts in the Vietnamese Mekong Delta: A long-term spatiotemporal analysis

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ABSTRACT

The Vietnamese Mekong Delta (VMD) has experienced severe morphological changes for decades, resulting in serious social, economic, and environmental consequences. Several natural and anthropogenic factors have contributed to the increasing rate of riverbed incision along the VMD. While previous studies have assessed riverbed incisions in specific affected regions or within limited timeframes, a comprehensive analysis of long-term spatiotemporal variations in incised sediment volumes across the entire delta has been lacking. This study quantitatively evaluated the spatial and temporal morphological changes in the VMD utilizing bathymetric data from 1998 to 2020. Additionally, susceptibility zones, categorized into seven classes for incised and accreted sediment volumes, were delineated considering the influence of sand mining activities. Furthermore, this study pioneers the quantification of sand mining contributions to riverbed incisions along the VMD. The analysis revealed pronounced and irregular morphological alterations in the delta channels over the 22 years of the study. The estimated net annual incision volumes for the entire region were -119 Mm^3/year, −69 Mm^3/year, and -66 Mm^3/year for the 1998–2005, 2005–2017, and 2017–2020 time intervals, respectively. Between 2017 and 2020, the dynamic processes intensified notably, with some areas experiencing either high incision (up to −13 m/year) or high accretion (up to 11 m/year). Intriguingly, most incise-prone areas were partly situated within regions associated with sand mining. The contribution of licensed sand mining to annual net riverbed incisions increased from 27.7 % in 2005–2017 to 35.3 % in 2017–2020. This study highlights the influence of sand mining on exacerbating the vulnerability of different areas within the VMD and provides valuable insights for effective sediment management strategies.

1. Introduction

River deltas are densely populated and biologically diverse regions of immense global importance that play vital social, economic, ecological, and environmental roles (Chen et al., 2022). Recently, climate change, in terms of rising sea levels, increased flood occurrences, and prolonged droughts, has presented a substantial threat to deltas worldwide. However, the detrimental consequences of these factors are markedly exacerbated by human interventions (Syvitski et al., 2009; Evans, 2012; Brunier et al., 2014). Anthropogenic activities directly impact the regulation of water discharge and reduce sediment supplies, considerably influencing the morphology of many of the world's deltas. As such, the morphological dynamics of deltas can be considered indicators that reflect the extent and scale of these activities poised to imperil delta

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stability (Brunier et al., 2014). The effects of these anthropogenic activities can manifest across various spatiotemporal scales, resulting in adverse repercussions on landforms, aquatic ecosystems, and the intrusion of salinity into river delta systems (Binh et al., 2022). The Vietnamese Mekong Delta (VMD) stands as no exception.

The VMD is a region of immense significance, not only to Vietnam but also to the global ecosystem (Sakamoto et al., 2009; Day et al., 2016; Borges et al., 2018; Dang et al., 2021). Its significance spans several dimensions, including its pivotal role in agro-aquaculture production (Binh et al., 2018; Park et al., 2022a) and biodiversity conservation to its impact on the livelihoods of 19 million people (Ziv et al., 2012; Quan et al., 2018). However, despite being an invaluable region, the VMD faces significant challenges arising from anthropogenic activities. On the one hand, its flow regime has been significantly altered, resulting in a notable reduction in the suspended sediment load (SSL) in the delta (Kummu and Varis, 2007; Kondolf et al., 2014; Lu et al., 2014; Binh et al., 2020). The construction of six dams in the Lancang cascade within the upper Mekong basin has led to a substantial SSL reduction ranging from 50 % to 94 % along the lower Mekong River (Kummu et al., 2010; Kondolf et al., 2014; Manh et al., 2015). Manh et al. (2015) examined the combined influence of hydropower development, climate change, and the effects of sea level rise and deltaic subsidence on sedimentation patterns in the VMD for a baseline (2000–2010) and a future (2050–2060) period. Their findings, derived from a numerical model, concluded that hydropower dams in the Mekong basin were likely the most impactful drivers of suspended sediment dynamic alteration in the VMD, contributing to a nearly 90 % reduction in delta sedimentation. Furthermore, completing sixty-four dams across the Mekong basin caused a severe reduction in the SSL by 74 % within the VMD (Binh et al., 2020). Binh et al. (2022) predicted that the total net incision volume from 2017 to 2026 would be approximately 2472 and 3316 Mm^3 under 18 % and 85 % suspended sediment reduction scenarios, respectively, because of river damming, threatening delta sustainability.

On the other hand, the VMD has undergone an evolution in sand mining activities in recent years to meet the growing demand for construction materials (Thao et al., 2014). The impact of these activities on the VMD is multifaceted, encompassing both local and broader consequences (Gruel et al., 2022; Lau et al., 2023). Locally, these activities contribute significantly to riverbed incision and riverbank erosion (Binh et al., 2022; Lau et al., 2023; Yuen et al., 2024), hence altering the natural balance of sediment transport and exacerbating the overall degradation of the delta system on a broader scale (Binh et al., 2022; Xin et al., 2024). Mining activities escalated from 7.75 Mm^3/year in 2012 (Bravard et al., 2013) to 29.3 Mm^3/year in 2018 (Jordan et al., 2019). It is worth noting that these values are likely underestimated compared with an average volume of 42 Mm^3/year in 2015–2020 (Gruel et al., 2022) and 45.73 Mm^3/year in 2015–2022 (Kumar et al., 2024), considering illegal mining activities.

Overall, anthropogenic activities have caused severe morphological degradation in the VMD (Binh et al., 2022). This morphological degradation engenders heightened erosion of riverbanks. Between 1988 and 2020, the average rates of accretion in area and width were 2.4 km^2/year and 5.2 m/year, respectively, exceeding the average erosion rates of 2.1 km^2/year and 3.5 m/year along the VMD. However, riverbank erosion has remained extensive, with an average length of 620 km/year, affecting 43 % of the riverbank length across the delta (Vu et al., 2024). This erosion poses a significant threat to agricultural land and settlements along these riverbanks (Hackney et al., 2020; Binh et al., 2022; Park et al., 2022a; Vu et al., 2024). For example, a recent media report highlighted that the collapse of 1808 houses in the VMD between 2018 and 2020 was attributed to extensive sand mining, which resulted in economic losses totaling USD 8.6 million (Lau et al., 2023). Furthermore, these changes can exacerbate salinity intrusion into freshwater areas, detrimentally impacting agriculture and the availability of potable water sources (Eslami et al., 2019; Binh et al., 2021; Park et al., 2022b). Morphological transformations within the delta can also have adverse effects on the aquatic ecosystem, disrupting fish habitats and biodiversity (Ficke et al., 2007; Padmalal et al., 2008; Ziv et al., 2012; Torres et al., 2017; Zou et al., 2019). Ultimately, the livelihoods of millions of people who rely on the delta for agriculture and aquaculture are poised to be significantly and detrimentally affected (Padmalal et al., 2008; Ziv et al., 2012; Tessler et al., 2015; Park et al., 2022a).

These alterations in riverbed morphology have been highlighted by research findings in various regions and time intervals within the VMD. For instance, Brunier et al. (2014) reported a significant and widespread deepening of the channel beds of both the Tien and the Hau Rivers from 1998 to 2008, resulting in a massive loss of bed material, estimated at 200 Mm^3 of eroded volume. The initial findings of Thuy et al. (2020) indicated that erosion is more pronounced and severe in the upper Tien River, upstream of My Thuan, with relatively lower impacts in estuaries. Jordan et al. (2020) reported that hydropower dams, exacerbated by sand mining, exert the most significant influence on riverbed incision, whereas the impact of sea level rise is comparatively lower. While these findings offer crucial foundational insights into various facets of riverbed incisions under the impact of human interventions, it is imperative to recognize their extent limitations, as they capture only a fraction of the actual morphological changes occurring across the entire VMD. Previous studies have focused primarily on either the lower VMD and its coastal areas (Xing et al., 2017; Tu et al., 2019) or specific regions within the upper VMD (Jordan et al., 2020; Binh et al., 2022). The key challenge in this context stems from the scarcity of long-term bathymetric data, which directly reflects the impact of human activities, specifically sand mining, on riverbed morphology degradation (Tate et al., 2002; Brunier et al., 2014; Lau et al., 2023).

As a result, some studies have focused solely on the broader ramifications of sand mining, as exemplified by Bravard et al. (2013) and Brunier et al. (2014), while others have focused on specific segments, as in Jordan et al. (2019). However, only a few studies have provided valuable insights into the local contribution of sand mining, such as the investigation conducted by Lau et al. (2023). Lau et al. (2023) revealed evidence of intensified sand mining activities in recent years by systematically examining the delta riverbed morphology from 2017 to 2022 via the same bathymetric datasets from 2017 and 2020 as our dataset. Nevertheless, owing to the limitations in the data used, particularly the deficiencies in the 2020 dataset, the failure to capture crucial cross-sectional features such as meanders, contractions, tails and heads of islands, confluences, and bifurcations hinders the provision of a reliable interpolated geometry for spatiotemporal variations across the delta. Hence, a more in-depth and holistic approach is imperative to fully comprehend the influence of mining activities on these changes, which reveals a conspicuous gap in prior research endeavors. By employing field data and geographic information systems (GIS), this study strives to provide a quantitative evaluation of the long-term spatial and temporal morphological changes in the VMD while also delineating susceptibility zones for incised and accreted sediment volumes.

Additionally, we quantified the spatiotemporal dynamics of sand mining contributions to these alterations. This study pioneers the quantification of sand mining contributions to riverbed incisions along the VMD by utilizing extensive measurements of long-term river bathymetry to provide insights into the impacts of human activities on morphodynamic processes. These findings underscore the compelling need for meticulous strategies aimed at preservation and sustainable management to safeguard the enduring prosperity of the VMD.

2. Study area

With a length of 4900 km, the Mekong River is the 12th longest river in the world (Gupta and Liew, 2007; Wang et al., 2011; Jordan et al., 2019). Originating on the Tibetan Plateau of China (Lu and Siew, 2006; Kummu et al., 2010; Lu et al., 2014), the Mekong River Basin covers an area of 795,000 km^2 (Fig. 1). It is characterized by an alluvial bed with a

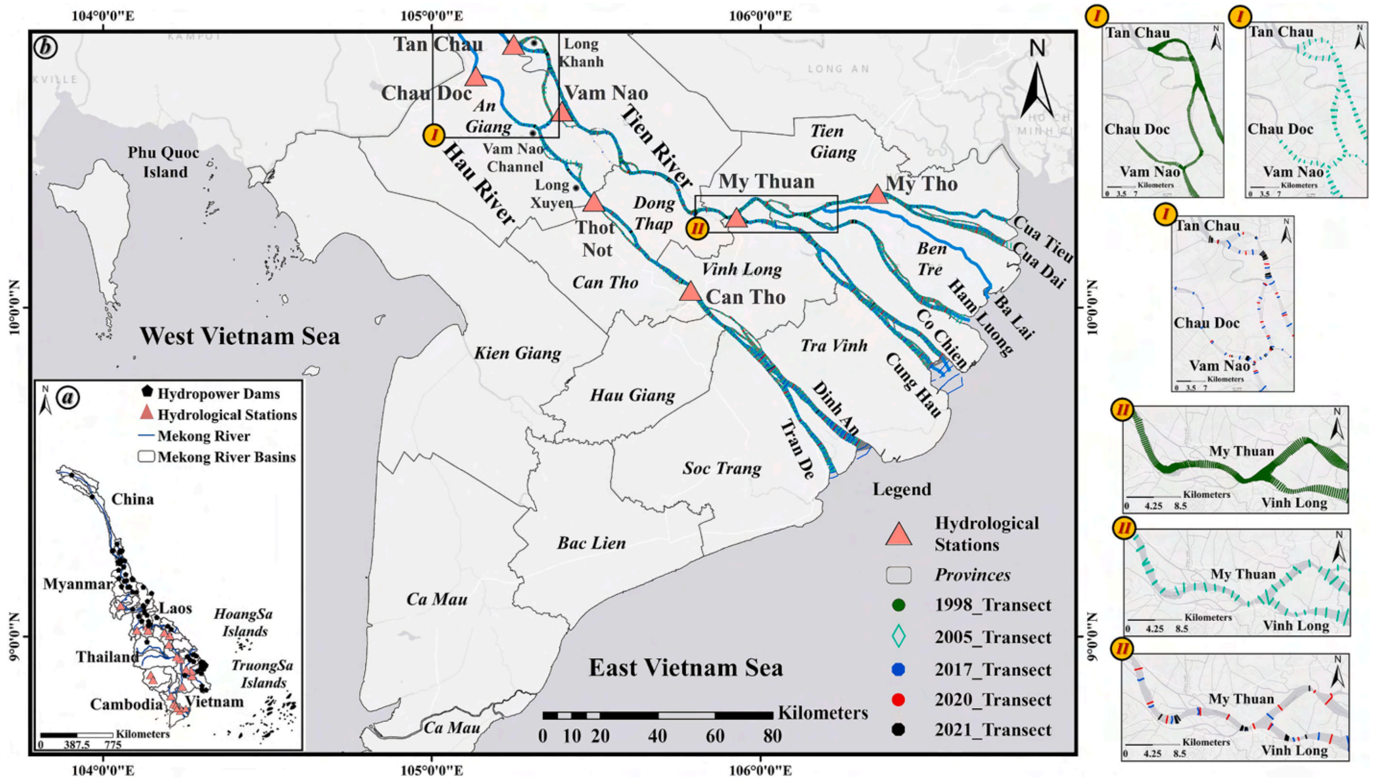

Fig. 1. (a) Map of the Mekong River Basin. (b) Map of the VMD study area showing field survey transects and tracks conducted in 1998, 2005, 2017, 2020, and 2021.

very mild slope of river networks, known as the Mekong Delta (Kondolf et al., 2014). The Mekong Delta stands as the world's third-largest delta (Anthony et al., 2015). It is divided into two parts: the Cambodian Mekong Delta (CMD), which extends from Kratie to the Vietnamese–Cambodian border, and the Vietnamese Mekong Delta (VMD), which extends from the Vietnamese–Cambodian border to the East Vietnam Sea. The Mekong Delta covers a total area of 63,000 km^2, with the CMD claiming approximately 24,000 km^2 and the remaining 39,000 km^2 residing within Vietnam's borders (Manh et al., 2014). The Tien and Hau Rivers enter Vietnam at the Tan Chau and Chau Doc stations. These rivers subsequently flow into the East and West Vietnam Seas through eight estuaries (Fig. 1). Historically, the Tien River accounted for approximately 80–95 % of the total discharge, whereas the Hau River contributed the remaining 5–20 %. However, the Vam Nao Channel has realigned this balance to 51 % for the Tien River and 49 % for the Hau River (Hung et al., 2014). The boundaries of our study encompass nearly 600 km of the VMD, extending from its northernmost point at Tan Chau and Chau Doc to its southern coastline along the Vietnamese Sea, including the Co Chien, Cung Hau, Tran De, and Dinh An estuaries. This comprehensive scope enables us to thoroughly evaluate riverbed incision susceptibility across the entire delta.

The annual water discharge of the VMD ranges from approximately 300 to 550 km^3 (Darby et al., 2016; Binh et al., 2022). Meanwhile, the SSL varies from 40 to 167 Mt./yr (Kondolf et al., 2014; Nowacki et al., 2015; Binh et al., 2020). The VMD experiences a distinct seasonal flow regime shaped by a monsoonal climate, with two main seasons: the flood season (July–December) and the dry season (January–June). During these seasons, the suspended sediment concentration (SSC) in the VMD varies significantly, reaching peak levels in the flood season and considerably decreasing in the dry season. Notably, areas near the river mouth feature a turbidity maximum, characterized by the highest turbidity resulting from the turbulent resuspension of sediment and the flocculation of particulate matter (Wolanski et al., 1996; Allison et al., 2017). The interaction between the semidiurnal tide from the East Vietnam Sea and the riverine discharge from the Mekong River system drives this phenomenon.

The VMD occupies a unique location between the transitional area of a fluvial-dominated zone in the upstream region and a tide-dominated zone in the downstream region (Gugliotta et al., 2017). This demarcation line occurs at the My Thuan and Can Tho gauging stations. The riverbed elevations of the Tien and Hau Rivers exhibit significant variations, ranging from just a few meters near the river mouths to exceeding 30 m in the upper reaches (Wolanski et al., 1996; Nowacki et al., 2015).

In light of these morphological characteristics, conducting a rigorous analysis of riverbed alterations and the consequent incision and accretion dynamics of the delta is imperative.

3. Materials & methods

3.1. Bathymetric field measurements and data processing

To evaluate morphological changes, field bathymetric data were collected for 1998, 2005, 2017, 2020, and 2021 (Fig. 1). The riverbed elevations in 1998 were obtained from Thuyloi University and the Southern Institute of Water Resources Research, Vietnam. The 1998 bathymetric data originally provided by the Mekong River Commission were measured by a bifrequency echosounder (Brunier et al., 2014). The data collection covered all major rivers within the VMD, with cross-sectional measurements taken at intervals ranging from 300 to 500 m (Binh et al., 2021). The 2005 dataset was subsequently sourced from the Southern Institute of Water Resources Planning (SIWRP), encompassing 212 cross-sections spaced at intervals of approximately 1.5 km.

The 2017 bathymetric data collection was conducted in August and September of that year, covering approximately 570 km of the Tien and Hau Rivers and the Vam Nao Channel. The Japan-ASEAN Science, Technology, and Innovation Platform (JASTIP) of Kyoto University, Japan, supported the survey financially. This survey extended from Tan Chau and Chau Doc to the river mouths, including the Co Chien, Cung Hau, Dinh An, and Tran De distributaries. Riverbed elevations at 200 cross-sections were measured using a Teledyne RD Instruments Workhorse Rio Grande 600 kHz acoustic Doppler current profiler (ADCP) equipped with a Trimble GPS and processed utilizing Teledyne RD Instrument WinRiver II software. A detailed description of the measurement and data processing was reported by Binh et al. (2020) and Binh et al. (2021).

The bathymetric data for 2020 were collected throughout 2020 and 2021 and were sourced from the SIWRP. Using a Teledyne Odom Hydrotrac II, the survey included the collection of 212 cross-sectional tracks at 5 km intervals. The surveying of cross-sections downstream of My Thuan in the Tien River and Can Tho along the Hau River to the East Vietnam Sea, including the Tieu, Dai, Ham Luong, Cung Hau, Co Chien, Tran De, and Dinh An distributaries, commenced in October 2020. In contrast, measurements for areas upstream of My Thuan and Can Tho, encompassing the Vam Nao Channel, were conducted in March 2021.

Upon assessing the reliability of the 2020 dataset, we identified omissions of crucial cross-sectional features at the meanders, contractions, tails, and heads of islands, confluences, and bifurcations. These cross-sectional data at such locations are essential for geomorphological analysis and geospatial interpolation. Therefore, we integrated these data with the 2021 bathymetric dataset to create a reliable interpolated geometry for spatiotemporal incision/accretion analysis. Hereafter, we refer to the combined 2020 and 2021 datasets as the 2020 dataset for consistency.

The 2021 bathymetric data, managed by the Ministry of Agriculture and Rural Development (MARD), consists of 113 cross-sections. This data collection spans from Tan Chau to the river mouth of the Tien River and from just upstream of the Hau-Vam Nao confluence to the river mouth of the Hau River. Notably, the 2021 cross-sections were more densely concentrated in specific areas, including meandering sections (e.g., near Sa Dec in the Tien River and Can Tho in the Hau River), contraction sections (e.g., around Tan Chau in the Tien River and Long Xuyen in the Hau River), the tails and heads of islands (e.g., downstream of Long Khanh Island in the Tien River), confluence sections (e.g., between the Hau River and Vam Nao Channel), and bifurcation sections (e.g., the bifurcation of the Ham Luong and Tieu-Dai distributaries in the Tien River).

3.2. Generating bathymetric and susceptibility maps

All bathymetric datasets collected in 1998, 2005, 2017, and 2020 were initially in XYZ coordinates (point data) and were projected to WGS 1984 Universal Transverse Mercator, zone 48 N, using Vietnam's national datum at Ha Tien (Gulf of Thailand) as the reference. Our primary objective was to quantitatively assess the spatial and temporal morphological changes in the VMD, utilizing these bathymetric datasets (Fig. 2). Thus, the bathymetric point data were first interpolated and converted into raster format via ArcGIS®10. The interpolation technique was universal kriging with the exponential method using a kernel function. This approach was the most suitable after conducting 111 trials involving deterministic and geostatistical methods available within the Geostatistical Analyst module in ArcGIS®10 (Binh et al., 2020). The method employs a leave-one-out cross-validation method, which predicts each data point's value using the remaining data based on the exponential variogram and then calculates the root-mean-square error (RMSE) by comparing the predicted values to the actual observations. The RMSE values for the generated maps were 2.2 (1998), 0.70 (2005), 0.22 (2017), and 0.80 (2020). The resulting interpolated riverbed elevation maps for all years of the study period maintained a consistent spatial resolution of 30 m.

Subsequently, we assessed the morphological changes in terms of depth (m) and volume (m^3) for three distinct periods: 1998–2005, 2005–2017, and 2017–2020. This evaluation was conducted by calculating the digital elevation model (DEM) differences in riverbed elevation within these periods via the Geomorphic Change Detection

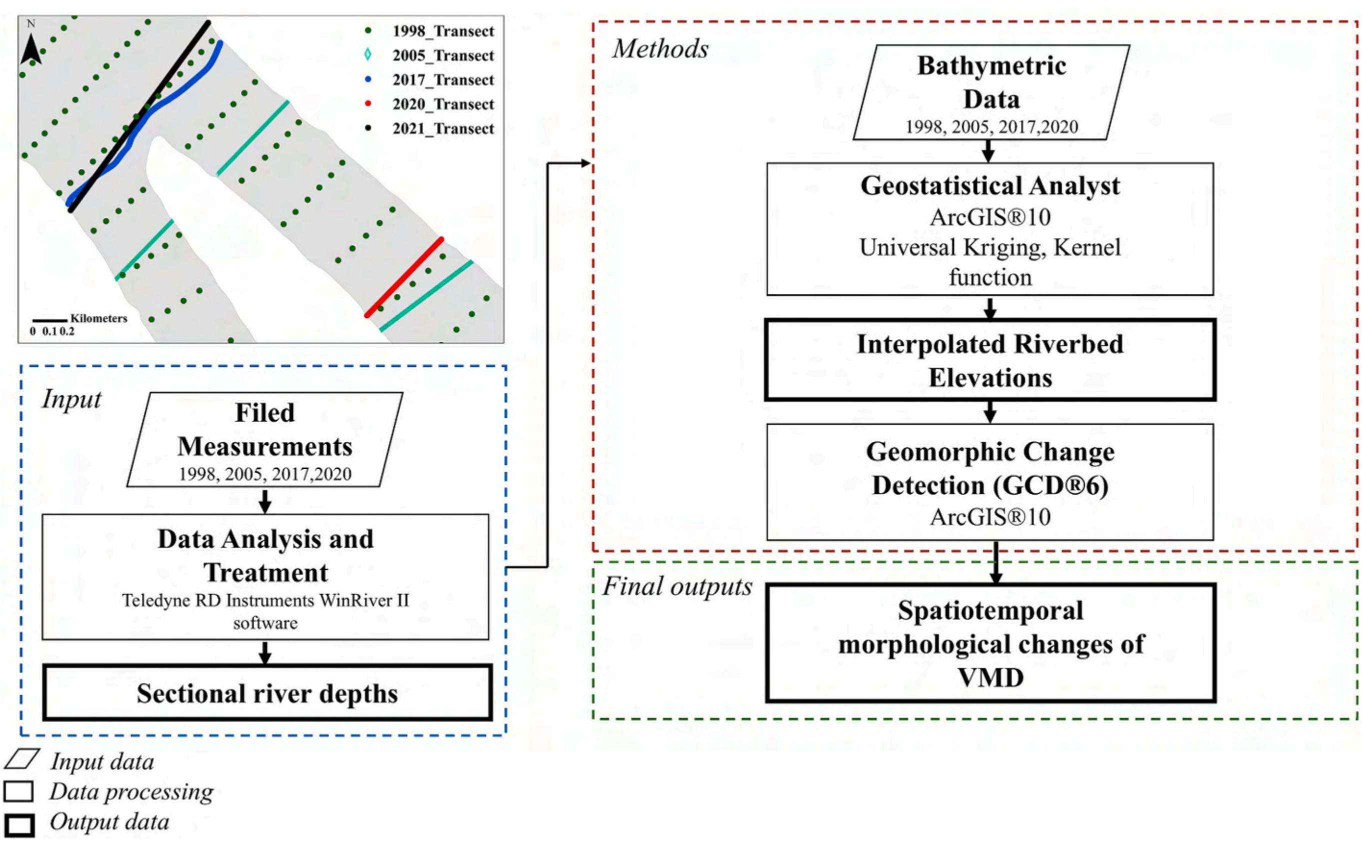

Fig. 2. Methodological framework used in this study.

(GCD®6) add-in within ArcGIS®10. To ensure the accuracy of the comparison and address potential errors stemming from instrument variations across different years, it is important to note that the depth uncertainty margin is ±0.2 m for every 10 m of depth (Brunier et al., 2014). In addition, we defined thresholds for detecting significant topographic changes corresponding to a 95 % confidence interval (Anderson, 2019). Consequently, differences in riverbed elevation and volume within this margin that did not exceed the defined thresholds were excluded from the comparison process. Considering the varying time spans across the three study periods, maps of the mean annual riverbed evolution (i.e., incision and accretion) were generated for each period and subsequently compared. Finally, the total annual riverbed incision and accretion volumes and the net volume differences were estimated for every 1 km segment along the main rivers of the VMD.

To delineate riverbed susceptibility zones (Fig. 2), we defined specific class ranges based on the differences in mean annual riverbed elevation across the three periods, with values ranging from <5 m to >-5 m. These rating values represent varying degrees of susceptibility to incision and accretion, with each class assigned a rating value on the basis of previous research (Roy et al., 2018; Khoi et al., 2020). The classification included seven categories: high incision (<−5 m/year), medium incision (−5 to −1 m/year), low incision (−1 to −0.5 m/year), stable riverbed (−0.5 to 0.5 m/year), low accretion (0.5 to 1 m/year), medium accretion (1 to 5 m/year), and high accretion (>5 m/year). Susceptibility maps play a pivotal role in comprehending the dynamic alterations in delta morphology, particularly when assessing the localized impacts of sand mining activities on these annual morphological changes. This holistic understanding is crucial for effective environmental management and sustainable development. Susceptibility maps can serve as a decision-support tool for policy-makers and stakeholders in addressing the challenges posed by sand mining activities in the Mekong Delta.

3.3. Sand mining data

Given the data limitations during the 1998–2005 timeframe, precise quantification of the impact of sand mining on morphodynamics is not feasible. Therefore, our examination focused solely on the influence of mining activities on morphological alterations in two periods: 2005–2017 and 2017–2020. To evaluate the influence of sand mining activities on the mean annual riverbed incision during the period of 2005–2017, we relied on data from Eslami et al. (2019). The sand mining data within the VMD were derived from licenses issued in 2015 by the Ministry of Natural Resources and Environment (MONRE) and underwent quality checks by the SIWRP. The extracted sand volume in this study (28 Mm^3) is four times greater than the previous estimate (7.75 Mm^3) for 2012 reported by Bravard et al. (2013). Notably, this dataset is based on information available at the time of its collection and may not capture the full temporal variability of sand mining activities in the VMD from 2005 to 2017. However, utilizing data from 2015 may provide a snapshot of sand mining activities and their effects on the annual morphological changes in the VMD during the corresponding period.

For the subsequent period of 2017–2020, we drew upon insights from provincial government reports detailing the annual volume of licensed sand mining issued in An Giang, Dong Thap, Vinh Long, Tra Vinh, Can Tho, and Soc Trang. The mining sites and sand budgets delineated in these datasets were validated through provincial government reports referenced in Yuen et al. (2024). Additionally, our boat-based field surveys conducted in August–September 2017 and April 2018 along almost 600 km of the VMD documented the same sand mining locations as those in the reports.

The influence of sand mining activities on the mean annual riverbed incision of the VMD was revealed via a mixed-method approach. This approach integrates spatially representative maps with high resolution and quantifies the contribution of sand mining to eroded sediment dynamics. The spatial maps presented the locations and extent of sand mining activities over the past two periods by employing GIS, while the quantification of sand mining's contribution to the morphological dynamics was estimated through the percentage of the total annual extracted sand volume over the total annual net changed volume, considering both the incision and accretion volumes (Zhang et al., 2022). The calculation equation is as follows:

$$P = (V_s/V_n)\% \quad (1)$$

where P is the percentage of the contribution of sand mining to the morphological alterations; V_s is the total annual extracted legal sand volume in Mm^3; and V_n is the total annual net volume of the differences in riverbed elevation, considering both the incision and accretion volumes in Mm^3. This approach comprehensively evaluates the intricacies of annual riverbed incisions in specific regions impacted by localized sand mining during the corresponding periods.

We acknowledge that the limited data from 1998 to 2005 imposes constraints on our ability to fully capture the temporal contributions of sand mining activities to changes in channel bed incision dynamics. Nevertheless, as highlighted in previous studies, the impact of sand mining during this earlier period is likely to have been less pronounced than that during more recent periods (2005–2017 and 2017–2020), where increased sand extraction has played a more substantial role (Kummu and Varis, 2007; Kummu et al., 2010; Kondolf et al., 2014; Manh et al., 2015; Binh et al., 2020, 2021, 2022). During the earlier period, sediment reduction due to river damming was a more dominant factor influencing riverbed morphodynamics.

Additionally, our analysis focuses primarily on legal sand mining activities, potentially overlooking the impact of illegal operations, which could further constrain our ability to comprehensively assess the interplay between sand extraction and morphological changes. However, according to Yuen et al. (2024), the annual rate of illegal sand mining extraction decreased from 2013 to 2018–2020 compared with the licensed extraction rates. Despite these constraints, our approach offers, for the first time, a solid foundation and valuable insights into the temporal localized impact and complex interactions of sand mining on riverbed dynamics in the VMD. This work can serve as a reference for policy-makers, particularly in light of the inclusion of illegal sand mining, which amplifies the impacts on riverbed dynamics.

4. Results and discussion

4.1. Evolution of mean riverbed elevations in the Tien and Hau Rivers

The analysis of mean riverbed elevations, derived from field surveys conducted in 1998, 2005, 2017, and 2020, revealed remarkable degrees of irregularity (Fig. 3), which aligns with prior research on enduring alterations in riverbed elevations, especially in deltaic regions, such as the Mekong Delta (Wolanski et al., 1996; Syvitski et al., 2005; Kondolf et al., 2014; Allison et al., 2017; Binh et al., 2020, 2021, 2022). These variations are often attributed to the highly dynamic and nonuniform nature of sedimentation in the delta, exacerbated by intensified anthropogenic activities, such as extensive sand mining (Lau et al., 2023). Sand mining, which involves extracting sediments from riverbeds, significantly alters natural sediment transport and deposition patterns, leading to reductions in riverbed elevation and resulting in irregular depressions or pockmarks (Kondolf, 1997; Padmalal et al., 2008; Sreebha and Padmalal, 2011; Hackney et al., 2021).

Brunier et al. (2014) documented a highly irregular system of pools and riffles along the Tien and Hau Rivers from 1998 to 2008, with the channels exhibiting significant deepening. This suggested that channel bed evolution during this 10-year study period was largely influenced by human activities rather than natural processes. These irregularities were attributed to the two main human interventions responsible for modern sediment deficits in deltas: dam construction and sand mining. The

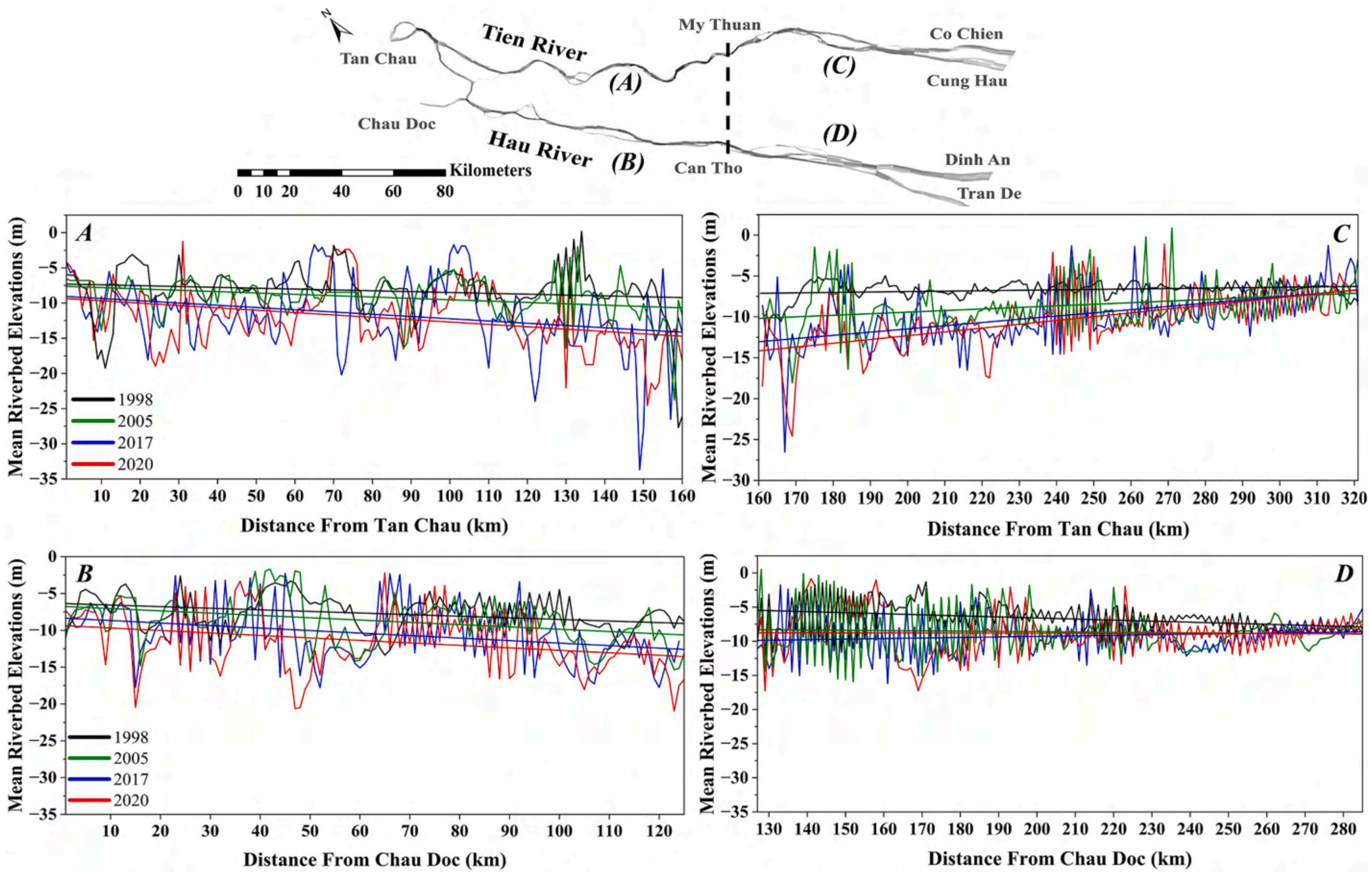

Fig. 3. Longitudinal profiles of the mean riverbed elevations at 1 km intervals across the VMD for 1998, 2005, 2017, and 2020. (A) Spanning from Tan Chau to My Thuan along the Tien River, (B) spanning from Chau Doc to Can Tho along the Hau River, (C) and (D) extending from My Thuan and Can Tho down to the southern coastline, respectively.

random nature of channel bed changes, coupled with the distribution of erosion areas, strongly pointed to extensive riverbed mining as the primary cause. Lau et al. (2023) further noted substantial variability in mean riverbed elevation for every 2.5 km segment across most river reaches between 2017 and 2020, driven predominantly by intensified sand mining activities. Both studies highlighted the profound impact of these activities on riverbed morphology, as evidenced by the jagged patterns observed in the delta's longitudinal profiles.

Our study revealed a discernible decline in the average riverbed elevation within the VMD throughout the 22-year study period (Fig. 3). Specifically, the mean riverbed elevations along the Tien and Hau Rivers, including the Tran De, Dinh An, Cung Hau, and Co Chien distributaries, in addition to the Vam Nao Channel, were approximately −7.15 m, −8.52 m, −10.21 m, and -10.57 m for 1998, 2005, 2017, and 2020, respectively. Furthermore, the lowest elevations were consistently identified in the upper reaches, specifically within the meandering stretch near Sa Dec city (approximately 3 km upstream of the My Thuan hydrological station). The recorded minimum elevations of −37.6 m in 1998, −46.3 m in 2005, −46.2 m in 2017, and -53.8 m in 2020 closely corroborated the findings presented by Brunier et al. (2014), where a deep pool of 45 m was discovered in 2008. On the other hand, Lau et al. (2023) reported that the lowest elevation in 2017 was −46.2 m, whereas, in 2020, it was −38.2 m within the same region, emphasizing the limitations of relying solely on the 2020 dataset. This discrepancy highlights the necessity of incorporating multiple datasets (i.e., 2020 and 2021) to capture crucial cross-sectional features such as meanders.

Remarkably, 2017 and 2020 revealed greater incision variability, mostly in the upper parts, than did previous years (Fig. 3A, B). The mean riverbed elevations for the upper reaches of the Tien River (from Tan Chau to My Thuan) were -8.26 m, −9.15 m, −11.61 m, and -12.05 m in 1998, 2005, 2017, and 2020, respectively (Fig. 3A). Meanwhile, for the upper reach of the Hau River (from Chau Doc to Can Tho), the mean riverbed elevations were -7.81 m, −8.73 m, −10.46 m, and -11.49 m for the same years (Fig. 3B). These findings underscore the existence of significant spatial disparities in riverbed elevations, with deeper areas predominantly localized in upstream regions (Lau et al., 2023).

In contrast to those in the upper reaches, the elevations in the lower reaches were generally higher and more regular (Brunier et al., 2014; Lau et al., 2023). The longitudinal profiles of the lower reaches experienced a coherent increasing trend as they progressed toward the East Vietnam Sea (Fig. 3C, D). The mean riverbed elevations for the lower reach of the Tien River (from My Thuan to the river mouth along the Cung Hau and Co Chien distributaries) were -6.67 m, −8.61 m, −9.87 m, and -10.32 m in 1998, 2005, 2017, and 2020, respectively (Fig. 3C). Similarly, for the lower reach of the Hau River (from Can Tho to the river mouth along the Tran De and Dinh An distributaries), the mean riverbed elevations were -6.61 m, −8.63 m, −9.25 m, and -8.83 m, respectively, for the same periods (Fig. 3D). However, for each individual year, the longitudinal profile displayed a slight upward trend, with elevations tending to increase slightly along the profile of the lower reaches within the estuarine sections of the Tien and Hau Rivers. This spatial pattern corresponds with the established concept of delta progradation, in which sediment accrual in the coastal regions of the delta induces mostly an upward elevation trend within the estuarine vicinity (Wolanski et al., 1996; Syvitski et al., 2005; Nowacki et al., 2015; Zhang et al., 2018; Obodoefuna et al., 2020). Therefore, while the riverbed deepened over time, the spatial upward trend within each year reflected localized sediment accumulation processes that were consistent with delta progradation.

Overall, recently, the Tien and Hau Rivers divulged a conspicuous downward trajectory in their upper reaches, mostly transitioning into an upward trend toward the estuary (Binh et al., 2018; Lau et al., 2023). This heightened dynamic, particularly in recent years, has arisen primarily from the ongoing interplay of various factors, notably human interventions, emphasizing their considerable influence on delta morphological changes (Kondolf et al., 2014; Hackney et al., 2020; Binh et al., 2022; Lau et al., 2023).

4.2. Spatiotemporal dynamics of riverbed morphology in the VMD

4.2.1. Entirety of the VMD

The bathymetry maps generated for the three periods spanning from 1998 to 2020 provided a comprehensive overview of riverbed evolution throughout the entire VMD (Fig. 4). The analysis unveiled that the average annual rates of riverbed incision along the thalweg were -0.19 m/year from 1998 to 2005, −0.11 m/year from 2005 to 2017, and -0.10 m/year from 2017 to 2020. Additionally, the net annual incision volume across the entire VMD was estimated to be −119 Mm^3/year, −69 Mm^3/year, and -66 Mm^3/year during these corresponding periods. These findings underscore the substantial incision and sediment loss experienced within the VMD.

Our holistic investigation revealed that riverbed incisions were not limited to specific locations, such as thalwegs or cross sections, but were conspicuously evident throughout the Tien and Hau Rivers across the three distinct periods (Fig. 4). However, it is noteworthy that the Tien River experienced more pronounced incisions than did the Hau River during each period (Fig. 5). This discrepancy is attributed to approximately 61–81 % of the SSL in the Hau River being redirected from the Tien River through the Vam Nao diversion channel during the flood season (Binh et al., 2022; Lau et al., 2023). Highlighting this point, the minimum net annual riverbed elevations estimated every 1 km along the Tien River were -1.58 m, −1.63 m, and -5.6 m in 1998–2005, 2005–2017, and 2017–2020, respectively. In contrast, the corresponding values for the Hau River were -1.23 m, −1.24 m, and -4.9 m in the three time periods.

Additionally, upon scrutinizing the channels of the Tien and Hau Rivers, incisions manifested throughout their lengths. Despite this, the proportion of alterations attributable to incisions diminished due to the increasing total annual volume changes (i.e., incision and accretion volumes). Influenced by the intricate dynamics of incision and accretion, the riverbed deepened, particularly during the last period. Specifically, the incisions along the entire length of the Tien River, including the Cung Hau and Co Chien distributaries, declined from 74 % to 72 % and further to 58 % when contrasted with the overall alterations stemming from incision and accretion across the designated time intervals. In comparison, incisions along the entire length of the Hau River Channel, including the Tran De and Dinh An distributaries, were estimated at 70 %, 68 %, and 53 % over the three periods. Nevertheless, as we shifted our focus to the upper reaches of the Tien and Hau Rivers, we observed a contradictory pattern in the proportion of alterations attributable to incisions, diverging from the overall trend.

4.2.2. Upper reaches of the VMD

Notably, the upper reaches of the Tien and Hau Rivers up to My Thuan and Can Tho presented significant incisions between 1998 and 2020, with an increasing trend observed across the three periods (Fig. 4; Fig. 6). The total net annual incision volume for the upper reach of the Tien River (from Tan Chau to My Thuan) was substantial, at −7 Mm^3, −27 Mm^3, and -37 Mm^3 for the periods of 1998–2005, 2005–2017, and 2017–2020, respectively (Fig. 6). Similarly, for the upper reach of the Hau River (from Chau Doc to Can Tho), the corresponding values were -6 Mm^3, −16 Mm^3, and -20.5 Mm^3.

Significantly, the deepest stretches along the Tien and Hau Rivers were predominantly found in their upper reaches, specifically around Sa Dec city for the Tien River and the proximity of Can Tho city and the river confluence near Long Xuyen for the Hau River. Several key factors contributed to this prominent incision. While natural factors, such as variations in precipitation patterns and river discharge, may impact

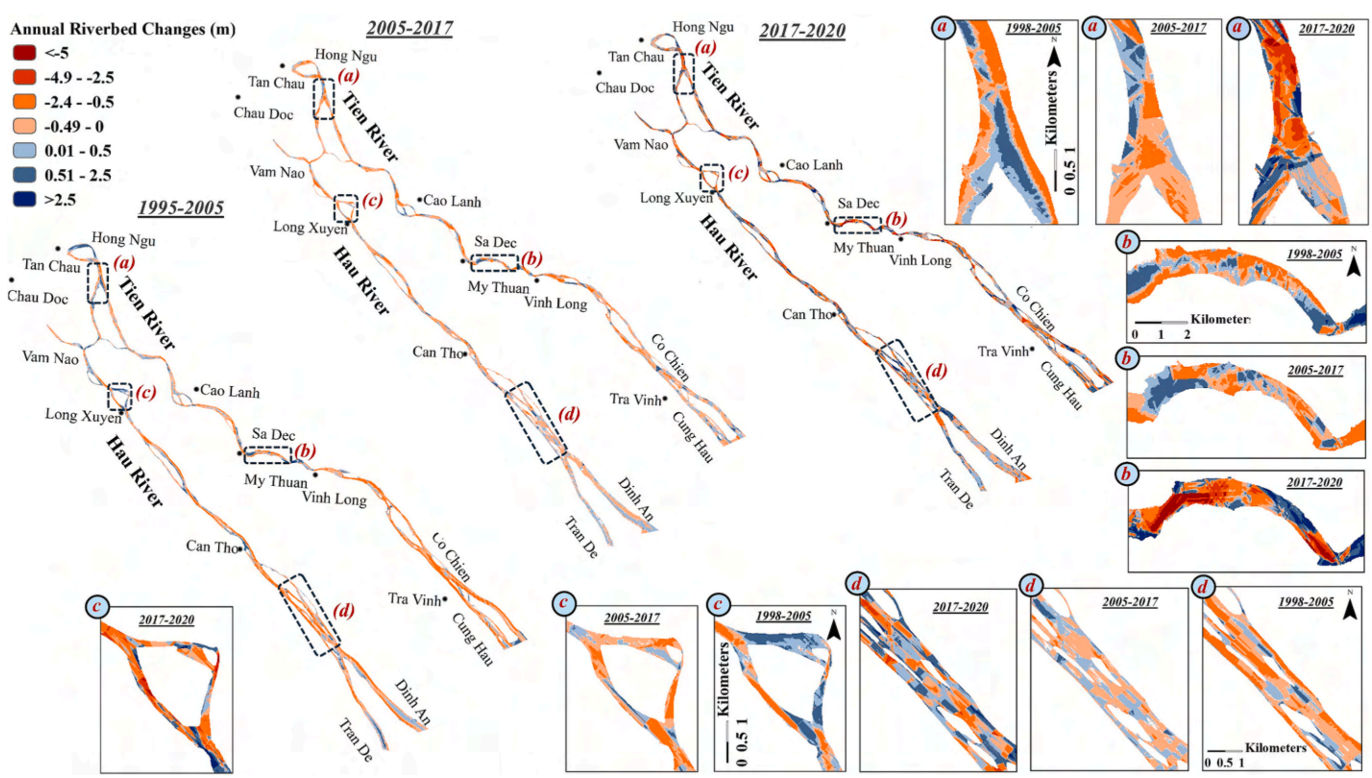

Fig. 4. Analysis of annual morphological changes: annual DEM differences for 1998–2005, 2005–2017, and 2017–2020 with typical zones: (a) approximately 12 km downstream of Tan Chau, (b) in the vicinity of the Sa Dec area, (c) upstream of Long Xuyen city, and (d) approximately 20 km downstream of Can Tho city.

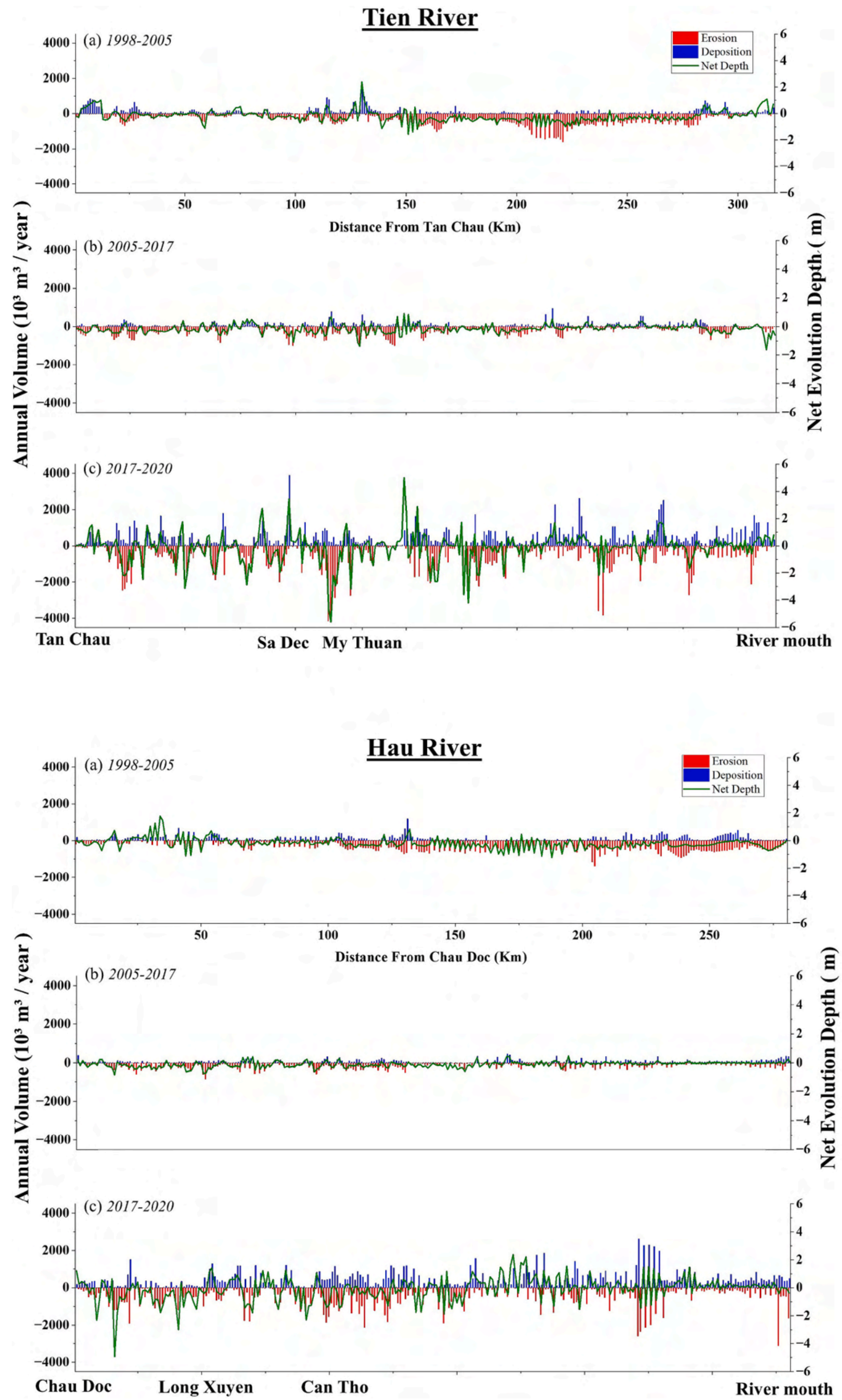

Fig. 5. Annual evolution of the volume (10^3 m^3) and net annual evolution of the depth (m) for every 1-km-long segment along the Tien and Hau Rivers from Tan Chau and Chau Doc, respectively, to the river mouths of the Tran De, Dinh An, Cung Hau, and Co Chien distributaries in 1998–2005 (a), 2005–2017 (b), and 2017–2020 (c).

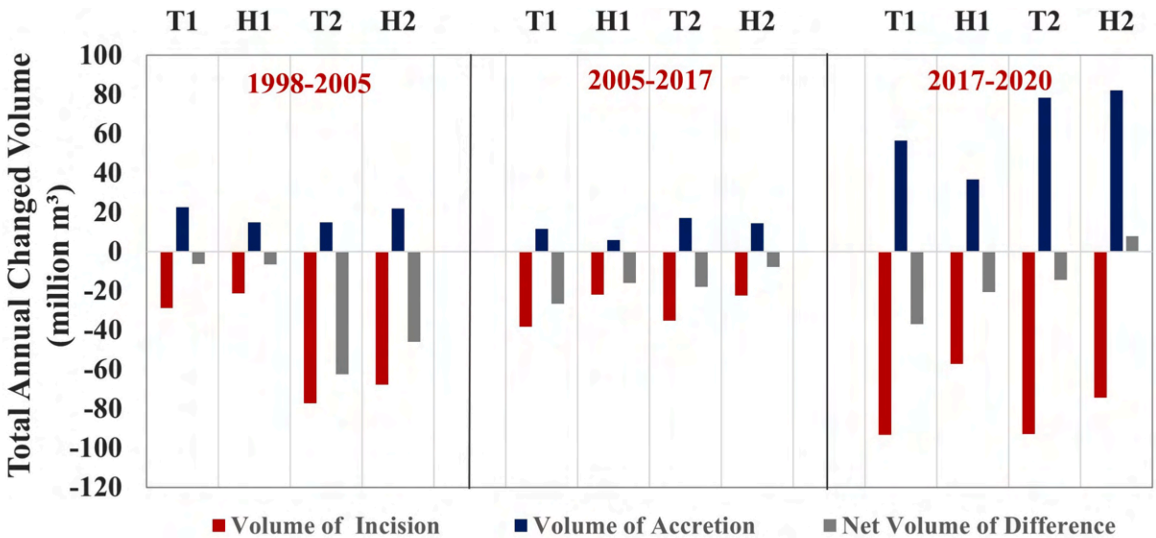

Fig. 6. Annual volume of incision, accretion, and net volume of difference in Mm^3 for riverbed evolution in the three time intervals of 1998–2005, 2005–2017, and 2017–2020 across the respective reaches (T1) from Tan Chau to My Thuan along the Tien River, (H1) from Chau Doc to Can Tho along the Hau River, (T2) and (H2) from My Thuan and Can Tho down to the southern coastline, respectively.

sediment delivery rates to the delta, influencing incision and accretion dynamics, human interference has emerged as a primary driver. This atypical increasing trend in riverbed incision, diverging from the natural depositional environment of the VMD, points to substantial human interference (Nguyen et al., 2000; Lau et al., 2023). These activities, such as upstream damming and excessive sand mining, have disrupted natural sediment transport processes, resulting in accelerated incision rather than accretion in the deltaic environment (Kummu and Varis, 2007; Bravard et al., 2013; Kondolf et al., 2014; Thao et al., 2014; Jordan et al., 2019; Binh et al., 2022; Gruel et al., 2022; Lau et al., 2023). The flow released from these dams is sediment-hungry (Kondolf et al., 1997), intensifying the incision of riverbeds rather than facilitating sediment settling. For example, the completion of the Manwan dam in 1993 caused a substantial decrease in the sediment load of 160 Mt./year by 50 %. The impact of this reduction was further exacerbated in 2009 following the commencement of operations at the Xiaowan and Nuozhadu Dams, the two largest structures in the Lancang cascade (Binh et al., 2021). Concurrently, there has been a notable transformation in sand mining practices within the VMD, driven by the escalating need for construction materials (Thao et al., 2014). This shift has positioned sand mining as a primary factor in increasing sediment-eroded volumes (Lau et al., 2023). Between 2012 and 2018, mining activities exhibited a robust increase, surging from 7.75 Mm^3/year to 29.3 Mm^3/year. Even more alarming, a six-year study conducted by Gruel et al. (2022) from 2015 to 2020 reported an average extraction volume of 42 Mm^3/year, accounting for unauthorized mining activities. Furthermore, an analysis contrasting sand export to the ocean (Stephens et al., 2017) and sand influx into the VMD (Hackney et al., 2020) revealed a concerning trend: the sediment replenishment rate within the VMD approached zero. The interplay of all these factors resulted in an imbalance in sediment dynamics, causing the region to experience severe decreases in sediment supplies, exacerbating the challenge of erosion mitigation.

4.2.3. Lower reaches of the VMD

On the contrary, sediment accretion noticeably increased in the lower reaches of both the Tien and Hau Rivers, extending to their respective river mouths (Fig. 4; Fig. 6). The total annual net riverbed incision volume for the lower reaches of the Tien River (from My Thuan to the river mouth along the Cung Hau and Co Chien distributaries) was significant at -62 Mm^3, -18 Mm^3, and -14 Mm^3 for the distinct periods of 1998–2005, 2005–2017, and 2017–2020, respectively. Comparatively, for the Hau River (from Can Tho to the river mouth along the Tran De and Dinh An distributaries), the values were -46 Mm^3, -8 Mm^3, and 8 Mm^3 across the three time intervals (Fig. 6).

Despite the heightened incision in the upstream regions, this dramatic increase in sediment accretion in the lower reaches can be attributed to the complex interplay of various factors, such as natural hydrological and geomorphological processes. Specifically, the mean cross-sectional flow velocities in the upstream segments are greater than those in the downstream regions (Binh et al., 2018). As a result, the turbulent flow regime generated from these high velocities coupled with the elevated shear stress can lead to the entrainment of sediment particles from the riverbed into the water column (Sutherland, 1967; Dey et al., 2011), consequently raising the volume of eroded sediment. Conversely, in the lower reaches where the flow velocity is reduced, causing the dissipation of flow energy, sediments carried by the river are more likely to settle and be deposited onto the riverbed and banks rather than transported further downstream (Hamlington et al., 2012). As a result of these processes, a considerable portion of the deposited sediment in the lower VMD most probably originated from incisions occurring in the upper sections of the Tien and Hau Rivers (Syvitski et al., 2005; Obodoefuna et al., 2020).

Additionally, considering that the delta is situated between the transitional area of a fluvial-dominated zone in the upstream region and a tide-dominated zone in the downstream region (Gugliotta et al., 2017), the accumulation of sediment on the delta's frontal shoals serves to amplify the dissipation of tidal energy, subsequently leading to a reduction in the tidal prism and a weakening of tidal flows. This decrease in tidal current diminishes the system's effectiveness in flushing sediment to the sea, increasing accretion on shoals (Zhang et al., 2018). Generally, sediments transported downstream by river flows and eventually discharged into the sea tend to settle and accumulate at the river mouths. However, an interesting phenomenon occurs: this deposited sediment is not static but is instead resuspended and carried back upstream by the action of waves and tides (Wolanski et al., 1996; Nowacki et al., 2015). In summary, the observed patterns of sediment incision and accretion in the Tien and Hau Rivers underscore the complexity of the morphodynamic process and often nonlinear responses in riverbed evolution under the impact of natural and anthropogenic key factors.

4.2.4. Comparative overview: insights from previous studies

Given the complexity of morphological changes in the VMD and divergences in alternative hypotheses, methodological approaches, and data sources across different studies, initial disparities between previous findings and our own are apparent. Nevertheless, upon closer examination, the remarkable consistency in the results suggests convergence rather than disparity. For instance, Brunier et al.'s (2014) estimation of sediment losses in the Tien River (90 Mm^3) and the Hau River (110 Mm^3) over the ten years from 1998 to 2008, with a net annual incision volume along the VMD of approximately −20 Mm^3/year, compared with −119 Mm^3/year from 19,982,005 in our study, revealed notable disparities. However, considering the study area of Brunier et al. (2014), covering almost 250 km along the VMD, excluding the Cung Hau and Co Chien distributaries, which are smaller than our study area, our findings exhibit coherence. This is evident, particularly in light of the heightened incision patterns observed in the first period along the estuaries (Fig. 4; Fig. 6). For further validation, we scrutinized almost the same path as that examined in Brunier et al.'s (2014) study, utilizing our data from 1998 to 2005. This analysis yielded a total net volume difference of −135 Mm^3 from 1998 to 2005, with an annual rate of approximately −19.3 Mm^3/year, thus providing further support for our findings. Furthermore, our investigation revealed 74 % of incisions along the entire length of the Tien River from 1998 to 2005 (Fig. 5), while Brunier et al. (2014) documented a lower incidence of incisions, at 59 %, over a distinct 250 km stretch. However, as mentioned before, this discrepancy can be attributed to the exclusion of Cung Hau and Co Chien distributaries from their analysis. These distributaries, according to our findings, were identified as areas primarily affected by riverbed incisions, especially during the first period (Fig. 4; Fig. 6). Intriguingly, in Brunier et al.'s (2014) study, the Hau River exhibited greater erosion, with 70 % of its length being incised, aligning with our findings (70 %) (Fig. 5), as their examination of the Hau River extended to the river mouth, which is similar to our study.

On the other hand, Lau et al. (2023) reported a 72 % incidence of incisions along a 200 km stretch of the Tien River from 2017 to 2020, with substantial sediment losses in the upper reaches totaling 139 Mm^3. While downstream in the Co Chien branch, sediment losses of 87 Mm^3 were recorded, contributing to almost total net annual losses along the Tien River, which amounted to 75 Mm^3/year. Conversely, our analysis unveiled a slightly lower incidence of incisions, at 58 %, along a 300 km segment of the Tien River, alongside a reduced total net annual sediment loss of 50 Mm^3/year during the same period (Fig. 5). Meanwhile, 47 % of the Hau River experienced incisions from 2017 to 2020, with sediment losses totaling approximately 127 Mm^3 across its upper reaches between 2017 and 2022, as illustrated by Lau et al. (2023). However, our examination revealed a slightly greater incidence of incisions, at 53 %, along the Hau River during the last period (Fig. 5). Therefore, acknowledging the methodological differences, including defining variations in longitudinal profiles, generating bathymetric maps, and utilizing combined datasets from 2020 and 2021 in our study compared with utilizing the 2020 data solely as in Lau et al. (2023), it is essential to recognize that these variances impact the absolute comparison of results, despite the use of the same datasets from 2017 and 2020 for both studies. Nonetheless, our study's main conclusions align with those of Lau et al. (2023) regarding the riverbed's primary accretion/incision pattern along the VMD. Specifically, consistent with Lau et al.'s (2023) findings, we observed that the Tien River experienced more pronounced incisions than did the Hau River from 2017 to 2020. Furthermore, our assessment revealed significant riverbed deepening and sediment losses, particularly in the upper reaches of both rivers compared with their lower reaches, in line with Lau et al.'s (2023) study. Moreover, Lau et al.'s (2023) study provided compelling evidence of sand mining intensification in the VMD from 2017 to 2020, a phenomenon that will be further supported through our findings in the subsequent section.

4.3. Riverbed incision susceptibility under the impact of sand mining activities

The sediment incision and accretion dynamics in the VMD exhibited significant variability across the three distinct periods. While the first two periods (i.e., 1998–2005 and 2005–2017) displayed relatively stable conditions, the third period experienced pronounced changes. The 2017–2020 period was characterized by alternating trends of incision and accretion at annual net riverbed elevations, with varying susceptibility levels ranging from low to medium to high (Fig. 7). In 1998–2005, 60.7 % of the VMD area was stable, with an equal balance of riverbed incision and accretion. Areas with low susceptibility levels to riverbed incision and accretion accounted for 22.7 % and 7.5 % of the region, respectively, indicating minimal risk. The percentage of riverbeds susceptible to medium levels of incision was 7 %, and that susceptible to accretion was 2.1 %. In the subsequent period of 2005–2017, the stability percentage increased to 80.3 %. This increase coincided with a decrease in areas under low susceptibility to riverbed incision and accretion, dropping to 12.1 % and 4.7 %, respectively. Areas with medium susceptibility levels for riverbed incision diminished significantly to 2.4 % and 0.5 % for riverbed accretion.

In contrast, the most recent period, 2017–2020, marked a reversal of these trends. The percentage of stable areas declined to 42.3 %, accompanied by a significant boost in areas susceptible to medium levels of incision and accretion, reaching 19.5 % and 16.4 %, respectively. Low susceptibility levels of the entire VMD to riverbed incision and accretion were 10.2 % and 10.5 %, respectively. High susceptibility levels to riverbed incision and accretion were also observed, albeit at lower percentages (0.8 % and 0.3 %).

It is evident that the period from 2005 to 2017 had the highest percentage of stable areas along the VMD compared with 1998–2005 and 2017–2020 (Fig. 7). This shift in stability was attributed to the changes in sediment dynamics in the upper and lower reaches of the VMD. In the upper reaches (i.e., T1 and H1), the susceptibility shifted from low accretion in 1998–2005 to stability in 2005–2017, driven by the increasing trend in riverbed incision, which reduced the percentage of areas experiencing low accretion in 2005–2017. Conversely, in the lower reaches (i.e., T2 and H2), susceptibility was transmitted from low incision to stability due to the rising pattern of accretion, as previously

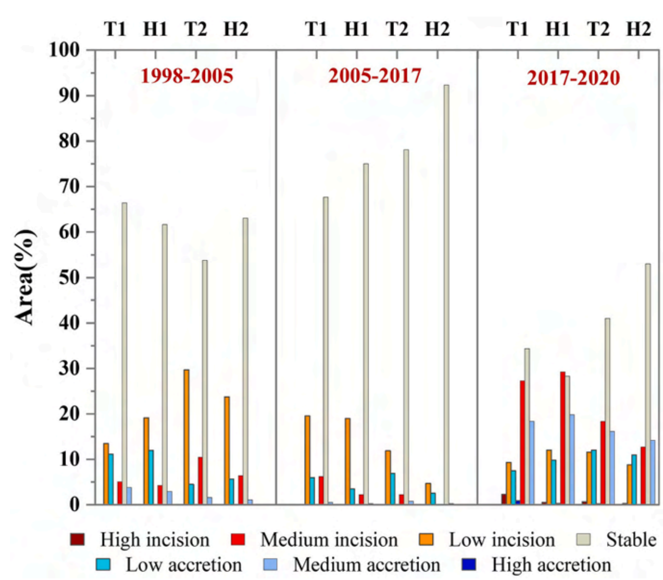

Fig. 7. Area percentages of riverbed susceptibility zones in the three time intervals of 1998–2005, 2005–2017, and 2017–2020 across the respective reaches: (T1) from Tan Chau to My Thuan along the Tien River, (H1) from Chau Doc to Can Tho along the Hau River, and (T2) and (H2) from My Thuan and Can Tho down to the southern coastline, respectively.

mentioned, which decreased the percentage of areas suffering from low incision in 2005–2017 (Fig. 7). The annual incision and accretion rates in these periods (i.e., 1998–2005 and 2005–2017) mostly ranged within ±1 m/year (Fig. 8). However, during 2017–2020, a significant reduction in the percentage of stable areas and a dramatic shift from low to medium susceptibility for both incision and accretion occurred, with a small percentage experiencing either high incision or high accretion (Fig. 7). For example, downstream Sa Dec city was highly susceptible to incision, with an annual alteration rate of −13 m/year, while the vicinity of Long Xuyen city witnessed high accretion, peaking at 11 m/year (Fig. 8).

These findings revealed a complex and unstable pattern in sediment dynamics within the VMD. The initial stability observed in the earlier periods gave way to increased stability and reduced susceptibility to incision and accretion, particularly in 1998–2005 and 2005–2017. On the other hand, the most recent period (i.e., 2017–2020) experienced a decline in stability and a resurgence of susceptibility levels, indicating a shifting trend in sediment dynamics, shedding light on the escalating influence of human interference. Our study specifically investigated the local impact of sand mining activities on the morphodynamics of the VMD. The analysis of riverbed incision susceptibility unveiled a relation between sand mining and morphological alterations, which was particularly evident in the changeable patterns of incision and accretion.

Our analysis discerned a profound contribution of sand mining to the total annual net volume of riverbed changes within the VMD. This influence became particularly evident when considering the licensed sand extraction volume, which totaled 19.1 Mm^3/year in 2015 within 600 km of our study area of the VMD (Eslami et al., 2019). Subsequently, provincial government data unveiled an average annual extracted licensed volume of 23.3 Mm^3/year across the same area between 2017 and 2020. This surge in sand mining activities (Yuen et al., 2024) significantly escalated the contribution of sand mining to the annual net riverbed alterations, soaring from 27.72 % during the second period of 2005–2017 to 35.3 % in the third period of 2017–2020. Our assessment corroborates the findings of Binh et al. (2021), revealing a similar trend of increased sand mining contributions to riverbed incisions. Specifically, Binh et al. (2021) demonstrated a rise from 23.4 % to 25.6 % in the sand mining contribution during the periods 1998–2014 and 2014–2017, respectively, along the upper reach of the Tien River (from Tan Chau to My Thuan).

Consequently, the remaining percentages in our analysis (i.e., 72.28 % in 2005–2017 and 54.7 % in 2017–2020) predominantly stem from the diminished sediment supply from the Mekong basin due to river damming, which has caused extensive riverbed incision in the VMD (Binh et al., 2020, 2021). However, areas affected locally by sand mining activities (Fig. 8) experienced heightened susceptibility to incisions (Lau et al., 2023; Yuen et al., 2024). These findings imply that while dam-induced sediment supply reduction primarily triggers riverbed incisions on a larger scale across the delta, sand mining predominantly contributes to the localized deepening of riverbeds. In other words, sand mining has intensified riverbed incision in the VMD, particularly in the wake of sediment supply reduction caused by upstream dams.

From earlier observations, a distinct trend emerged: the upper reaches of the VMD experienced increased incision over the studied periods, whereas the lower reaches displayed heightened levels of sediment accretion. This pattern is closely associated with the amplified sand mining activities upstream compared with downstream, which is evident across each period (Fig. 8). Notably, excessive sand extraction in areas such as the vicinity of Tan Chau, downstream of Hong Ngu along the Tien River, and along the Hau River, extending from Long Xuyen to Can Tho cities, manifested in the transition of susceptibility levels from low to medium, deepening the riverbed by almost 4 m/year during the last two periods (Fig. 8). Similarly, prominent sand mining hotspots along the Tien River, such as the Sa Dec and Vinh Long regions, have contributed to sediment depletion, thereby exacerbating susceptibility to incision (Brunier et al., 2014; Jordan et al., 2019; Gruel et al., 2022; Lau et al., 2023). Consequently, this intensified sand mining activity accelerated riverbed incision by >10 m/year in 2017–2020 compared with the preceding two periods (Lau et al., 2023).

These findings highlight the intensified erosional processes in recent years in the VMD, particularly in the upper reaches, emphasizing the growing impact of sand mining (Table 1). For example, in Dong Thap Province, the annual extracted sand volume surged from 9.5 Mm^3 in 2015 to 9.88 Mm^3 in 2017–2020, altering the susceptibility from low

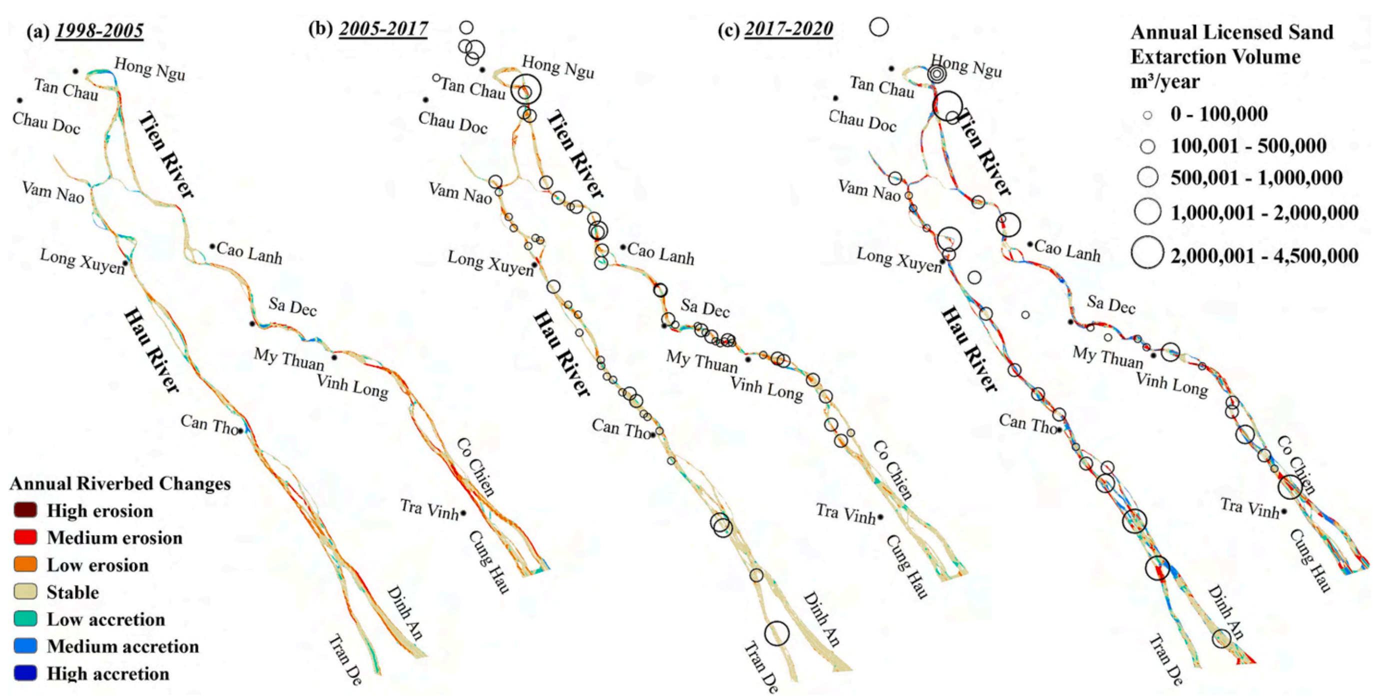

Fig. 8. Annual riverbed incision susceptibility maps for 1998–2005 (a), 2005–2017 (b), and 2017–2020 (c) with annual licensed sand extraction volumes in 2015 (shown in (b)) and between 2017 and 2020 (shown in (c)).

Table 1
Annual legal extracted sand mining volume per province (Mm^3/yr) (Eslami et al., 2019).

Province	2015	2017–2020
Dong Thap	9.5	9.88
An Giang	2	3.5
Vinh Long	1.5	4
Soc Trang	4	2.8

incision in some areas during 2005–2017 to medium incision in 2017–2020. Meanwhile, in An Giang Province, the annual extracted volume escalated from 2 Mm^3 in 2015 to 3.5 Mm^3 in 2017–2020, resulting in a similar shift in susceptibility levels. In Vinh Long Province, the annual extracted volume rose from 1.5 Mm^3 in 2015 to 4 Mm^3 between 2017 and 2020, causing the susceptibility to change from stable, with low incision in some areas, to medium levels of incision.

Conversely, the reduction in sand mining activities in the lower reaches explained the alterations observed (Table 1). For instance, the annual volume of extracted sand in Soc Trang along the Hau River decreased from 4 Mm^3 in 2015 to 2.8 Mm^3 in 2017–2020. This decline led to variations in susceptibility, ranging from stable in most areas to low and medium accretion levels during the last two periods. However, limited incised-prone areas partly situated within regions affected by sand mining exhibited medium susceptibility to incision. This observation reinforces our understanding of the local influence of sand mining on riverbed deepening. For example, the Tra Vinh region shifted susceptibility from stable in 2005–2017 to medium levels of incision in 2017–2020, with elevation differences recorded at −5 m/year. Eventually, even though our analysis is limited to the legally extracted sand volume, the increase in sand extraction has heightened susceptibility to medium incision levels in recent periods. This is exemplified by an annual alteration rate of −5 m/year, which is indicative of the delta's evolving morphodynamics. In light of these findings, there is a reasonable assumption that those currently grappling with medium incisions, particularly in the upstream part of the delta, have a greater potential to endure high susceptibility to riverbed incisions.

4.4. Implications and strategic management approaches for riverbed incisions in the VMD

On the basis of our previous discussion, the ascension in regions facing high incisions is poised to intensify the formation of scour holes, a direct consequence of significant bed incisions that entrap sediment within these depressions, thereby exacerbating riverbank erosion (Binh et al., 2022; Lau et al., 2023). This notion aligns with the observed trends of riverbank changes in the Tien and Hau Rivers, where erosion has steadily increased over time (Khoi et al., 2020; Kim et al., 2023; Vu et al., 2024). For example, Vu et al. (2024) reported that between 1995 and 2002, the average eroded width across the entire delta was 4.1 m/year, with an erosion area of 1.6 km^2/year, whereas accretion averaged 4.3 m/year, with an area of 2.7 km^2/year. Nevertheless, from 2015 to 2020, erosion intensified to 4.4 m/year, with an area of 3 km^2/year, while accretion remained steady at 4.3 m/year but covered a smaller area of 1.6 km^2/year (Vu et al., 2024). Interestingly, the areas of severe bed incision identified in our study closely correspond to those of riverbank erosion reported by Vu et al. (2024). Our 2022 field survey in Vinh Long, upstream of Tra Vinh, and the Ham Luong estuary further substantiates this, revealing instances of recent bank erosion near previously identified lowered and irregular riverbeds (Lau et al., 2023), posing imminent threats to nearby agricultural terrains and human settlements. This underscores the urgent need for expedited strategies focused on preservation and sustainable management in the VMD to ensure enduring prosperity. However, prevailing efforts to safeguard communities from accelerating morphological changes through the construction of embankments, dikes (Brunier et al., 2014), groin fields, and revetments (Jordan et al., 2019), along with the promotion of revegetation (Hackney et al., 2020), may prove inadequate and financially burdensome over time (Lau et al., 2023).

This prompts a shift in focus toward more resilient mitigation. Notably, community engagement and policy reform have become pivotal in addressing the multifaceted challenges of riverbed alteration, sand mining, and riverbank erosion in the VMD, safeguarding both agricultural productivity and communities reliant on VMD resources (Pradhan et al., 2021). Empowering local communities, including farmers, fishers, and residents of riverine settlements, in decision-making processes related to river management is indispensable (Tri et al., 2023). This can be achieved through participatory approaches, such as community forums, citizen science initiatives, and inclusive consultations that solicit feedback and insights from diverse stakeholders. By involving local communities in planning and implementation processes, policy-makers can ensure that interventions are contextually relevant and socially equitable.

Additionally, increasing public awareness of the environmental, social, and economic implications of the worsening situation in the delta is crucial for fostering collective action and mobilizing support for sustainable management initiatives (Tri et al., 2023). On the other hand, policy-makers need to enact and enforce regulations that regulate sand mining activities, promote responsible resource extraction practices, and safeguard riverine ecosystems (Lau et al., 2023). This evolution in strategies not only protects communities in the VMD but also preserves this increasingly unstable and shrinking deltaic landscape (Schmitt et al., 2021).

In summary, while our study provides crucial insights, a more comprehensive research approach is needed to fully comprehend the complex interplay of natural and anthropogenic factors shaping the morphology of the Mekong Delta, including a precise quantification of the contribution of bank erosion to sediment budgets. Although our findings generally align with those of previous research (Brunier et al., 2014; Lau et al., 2023), notable discrepancies exist that necessitate further investigation. Specifically, variations in the accretion/incision patterns and volumes of riverbed alterations in some critical river sections emphasize the importance of utilizing ample bathymetric data for interpolation to derive accurate insights into morphological changes. Acknowledging the impracticality of achieving a highly detailed spatial resolution for the entire VMD, we stress the necessity of conducting measurements at critical sections, such as meanders, contractions, tails and heads of islands, confluences, and bifurcations. This targeted approach is essential for generating reliable interpolated geometry to facilitate comprehensive spatiotemporal examination of incision/accretion dynamics.

5. Conclusion

Our comprehensive 22-year study revealed pronounced irregularities in riverbed elevation throughout the entire VMD. Notably, distinct declines in average riverbed elevation were discerned for 1998, 2005, 2017, and 2020 across the VMD, recording approximately −7.15 m, −8.52 m, −10.21 m, and -10.57 m, respectively. Concurrently, the net annual incision volume throughout the VMD was estimated at −119 Mm^3/year for 1998–2005, −69 Mm^3/year for 2005–2017, and -66 Mm^3/year for 2017–2020. Our analysis further highlighted significant incisions in the upper reaches of the Tien and Hau Rivers, with an increasing trend over the years. The total net annual incision volume for the upper reach of the Tien River was substantial at −7 Mm^3, −27 Mm^3, and -37 Mm^3 for 1998–2005, 2005–2017, and 2017–2020, respectively. Similarly, for the upper reach of the Hau River, the corresponding values were -6 Mm^3, −16 Mm^3, and − 20.5 Mm^3. This trend is predominantly attributed to the ramifications of anthropogenic activities, such as sand mining and alterations in sediment transport dynamics resulting from dam construction. In contrast, sediment accretion manifested in the lower reaches. The total annual net riverbed incision volume for the lower reaches of the Tien River totaled −62 Mm^3, −18 Mm^3, and − 14 Mm^3 for the periods 1998–2005, 2005–2017, and 2017–2020, respectively. Comparatively, for the lower reach of the Hau River, the values were − 46 Mm^3, −8 Mm^3, and 8 Mm^3 across the three time intervals. These alterations were influenced by various factors, including natural hydrological and geomorphological processes, resuspended sediment transported by waves and tides, and upstream erosion dynamics.

In addition, a more pronounced incision was consistently observed along the Tien River than along the Hau River for each examined period. This disparity can be attributed to the redirection of the sediment supply from the Tien River to the Hau River and the increasing intensity of sand mining activities in the region. The contribution of licensed sand mining to annual net riverbed incisions surged from 27.7 % during 2005–2017 to 35.3 % in 2017–2020. This escalation in sand extraction has consequently led to a shift in the riverbed's susceptibility to medium incision levels, even when considering only the volume of the legally extracted sand. These findings suggest a reasonable inference that those currently grappling with medium and high incision susceptibility, particularly in the upstream part of the delta, have greater potential to exhibit high incisions in the future.

This study serves as a vital reminder of the ever-evolving morphology of the VMD, shaped by anthropogenic forces, with implications for delta stability in the future. These findings underscore the need for a holistic approach to manage and mitigate the impacts of these surging activities on the environment of the Mekong Delta and its inhabitants. This requires engaging with communities and reforming policies to address the multifaceted challenges faced by the VMD, safeguarding both agricultural productivity and communities reliant on the VMD's resources. In conclusion, while our study provides a comprehensive long-term examination of the morphological alterations within the Mekong Delta, further research is needed to fully elucidate the intricate interactions between natural processes and human activities. By continuing to investigate these complexities and implementing evidence-based management strategies, we can strive toward a more resilient and sustainable future for the Mekong Delta and its communities.

CRediT authorship contribution statement

Menna Farag Ahmed: Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Doan Van Binh:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Data curation. **Sameh Ahmed Kantoush:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Conceptualization. **Edward Park:** Writing – review & editing, Resources, Data curation. **Nguyen Luyen Phuong Doan:** Writing – review & editing, Resources, Data curation. **Luc Anh Tuan:** Writing – review & editing, Resources, Data curation. **Vuong Nguyen Dinh:** Writing – review & editing, Resources, Data curation. **Thi Huong Vu:** Writing – review & editing, Resources, Data curation. **Binh Quang Nguyen:** Methodology, Data curation. **Trieu Anh Ngoc:** Writing – review & editing, Resources, Data curation. **Nguyen Xuan Tung:** Writing – review & editing, Resources, Data curation. **Tetsuya Sumi:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Doan Van Binh reports financial support was provided by the Japan-ASEAN Science, Technology and Innovation Platform (JASTIP). Doan Van Binh reports financial support was provided by the Asia-Pacific Network for Global Change Research (APN). Nguyen Xuan Tung reports financial support was provided by the Vietnam Academy of Science and Technology (VAST). Binh Quang Nguyen reports financial support was provided by Japan Society for the Promotion of Science. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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