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DYNAMICS OF ESTUARINE CIRCULATION AND MORPHOLOGICAL ALTERATIONS: A CASE STUDY OF THE VIETNAMESE MEKONG DELTA

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ABSTRACT

Estuarine circulation is a fundamental characteristic in shaping estuarine dynamics, yet the interrelation between estuarine circulation and morphological alterations in tropical river systems such as the Vietnamese Mekong Delta (VMD) remains insufficiently investigated. Our study aims to address this gap by assessing short-term spatial variations in estuarine circulations within Dinh An and Co Chien distributaries during the 2016 dry season, a year marked by one of the worst droughts in the region. A one-dimensional hydrodynamic and advection-dispersion model (MIKE 11) was employed to analyze circulation variations based on nondimensional parameter space. Additionally, bathymetric datasets from 2017 and 2020 coupled with remote sensing techniques were utilized to scrutinize the relevance between estuarine circulation and morphological changes in the VMD. The analysis revealed that the semidiurnal tidal cycle significantly impacted the circulation patterns of both distributaries. Spatially, the circulation at 0 km and 25 km from the river mouth displayed distinct behavior: Co Chien's circulation pattern was influenced by severe morphological alterations in the riverbed elevations whereas, Dinh An maintained a relatively stable circulation pattern due to a stabilized riverbed. Moreover, during this dry season, Dinh An was classified as a salt wedge estuary, experiencing localized riverbank erosion intensified around the wedge areas where the suspended sediment concentration (SSC) was substantially lower than that in the freshwater zone. In contrast, Co Chien, classified as a strongly stratified estuary, exhibited more widespread riverbank erosion because of the shear stresses caused by stratified water layers across that segment. This study provides crucial insights into the interplay between circulation mechanisms and morphological evolution in the VMD,

offering a deeper understanding of morphological alterations and their broader implications for delta sustainability amidst changing environmental conditions.

Keywords: *Estuarine circulation, Riverbed incision, Riverbank erosion, Mekong delta*

1. Introduction

Estuaries are complex coastal systems where physical, chemical, and biological processes interact to define their ecosystem stability and morphological characteristics (Figueroa et al., 2022). Typically, classical estuaries exhibit a net near-bottom landward inflow that transports seawater into the estuary. This seawater is then transformed by estuarine mixing processes into a net near-surface seaward outflow, creating a bidirectional exchange flow known as estuarine circulation (Geyer & MacCready, 2014). These circulation patterns are significantly influenced by estuarine geomorphology, sediment transport dynamics, tidal forces, river hydrological systems, and climatic changes (Wolanski & Elliot, 2016). Recently, climate change, in terms of rising sea levels, increased flood occurrences, and prolonged droughts, has posed substantial threats to the estuarine environment and ecosystem globally. Yet, the detrimental consequences of these factors are markedly exacerbated by human interventions (Brunier et al., 2014). Anthropogenic activities such as land reclamation, excessive sand mining, and upstream river damming have dramatically altered sediment fluxes in estuaries, resulting in intrinsic global changes in estuaries dynamics (Jung et al., 2021; Wang et al., 2015). The Vietnamese Mekong Delta (VMD) is no exception, facing intensified challenges stemming from natural and human drivers (Ahmed et al., 2025).

The VMD is one of the world's most pristine and highly productive agro-aquaculture deltas (Binh et al., 2020; Ahmed et al., 2025), considering the rapid expansion of alternative farming of marine shrimp-rice, which has played an important role in boosting the income levels of local farmers (Anh et al., 2020). However, estuarine environments are increasingly vulnerable due to morphological degradation, which exacerbates saline water intrusion into freshwater zones, jeopardizing agro-aquaculture productivity and the purity of drinking water (Eslami et al., 2019). For instance, the 2016 drought, which caused catastrophic crop losses (~450-650 k ha) due to salt intrusion, exemplifies the severe consequences of these changes (Eslami et al., 2021). Such alterations in delta morphology pose challenges to aquatic ecosystems, imperiling fish habitats and overall biodiversity (Zou et al., 2019). For example, the decomposition of organic material in high turbidity zones can cause oxygen depletion, especially where mixing with oxygen-rich surface water is inhibited by vertical stratification (Abril et al., 1999). Ultimately, the sustenance of the vast population reliant on the delta's resources for farming and aquaculture hangs precariously in balance (Park et al., 2022). Research has extensively documented and investigated estuarine dynamics in the VMD, offering valuable insights into tidal forcing, stratification, circulation, and sediment transport mechanisms (Wolanski, 1998; Nguyen et al., 2018; Dang et al., 2019; Eslami et al., 2019; An et al., 2025). Nevertheless, a holistic assessment of the interplay between estuarine circulation and riverbed and riverbank evolution remains elusive. This gap hinders the development of effective management strategies for maintaining delta stability. Our study addresses this gap by examining short-term spatial variations in estuarine circulation in Dinh An and Co Chien distributaries, focusing on their interrelation with morphological changes. We evaluated circulation patterns under varying morphological conditions using a one-dimensional hydrodynamic model (MIKE11), bathymetric data, and remote sensing techniques. The findings will contribute to improved sediment management approaches and resilience planning for the VMD, addressing key challenges in estuarine sustainability.

2. Study Area

The Mekong Delta is segmented into two main regions: the Cambodian Mekong Delta (CMD), which extends from Kratie to the Vietnamese-Cambodian border, and the VMD, which stretches from the border to the East Vietnam Sea (Manh et al., 2014; Xing et al., 2017). As the Mekong River flows to Vietnam, it splits into the Tien and Hau Rivers, which start upstream of the Tan Chau and Chau Doc stations, respectively (Fig. 1). Further downstream, these rivers are divided into seven estuarine distributary channels (Fig. 1).

The VMD occupies a unique ecological and geographical location, straddling the transition zone between a river-dominated region upstream of the delta and a tide-dominated downstream region (Gugliotta et al., 2017). Despite geomorphological differences, all estuarine channels in the downstream region share similar tidal dynamics. They are mesotidal hyposynchronous systems with strong spring–neap tidal variations. Spring tides are predominantly semidiurnal with a tidal range of 3 m, while neap tides are influenced by diurnal tidal components with a range of 2 m, creating pronounced variability in tidal forcing (Eslami et al., 2021).

The hydrological regime of the VMD is primarily governed by a monsoonal climate, resulting in two distinct seasons: the flood season (July–December) and the dry season (January–June). During these seasons, the suspended sediment concentration (SSC) varies significantly, peaking during the flood season and declining sharply in the dry season. Intriguingly, the turbulent resuspension of this sediment near river mouths and the flocculation of particulate matter resulted in turbidity maxima in this region (Wolanski et al., 1998; 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.

It is worth noting that the riverbed elevations of the Tien and Hau Rivers exhibit significant variations, dropping from a few meters near their mouths to exceeding 30 meters upstream (Wolanski et al., 1998; Nowacki et al., 2015). Comprising primarily soft substrates, these riverbeds are vulnerable to upstream flooding, human interventions, and tidal forcing, contributing to accelerated riverbank erosion (Ahmed et al., 2024). In addition, escalating urbanization, expanding at approximately 18,000,000 m² annually along riverbanks and canal edges, intensifies the strain on these delicate banks. As a result, riverbanks are now more susceptible to collapse than they were in previous years.

Given these pressing concerns, conducting a rigorous analysis of estuarine circulation dynamics and the related consequent erosion of deltaic riverbeds and banks is imperative. In this study, as we focus on estuarine circulation during the dry season, we limit the timescale to specifically focus on the 2016 drought, a period of severe hydrological and morphological stresses induced by the 2015–2016 El Niño (Eslami et al., 2021). This extreme event led to prominent morphological degradation and heightened salinity intrusion, providing a valuable case study for assessing the governing mechanisms and their impact on the estuarine environment.

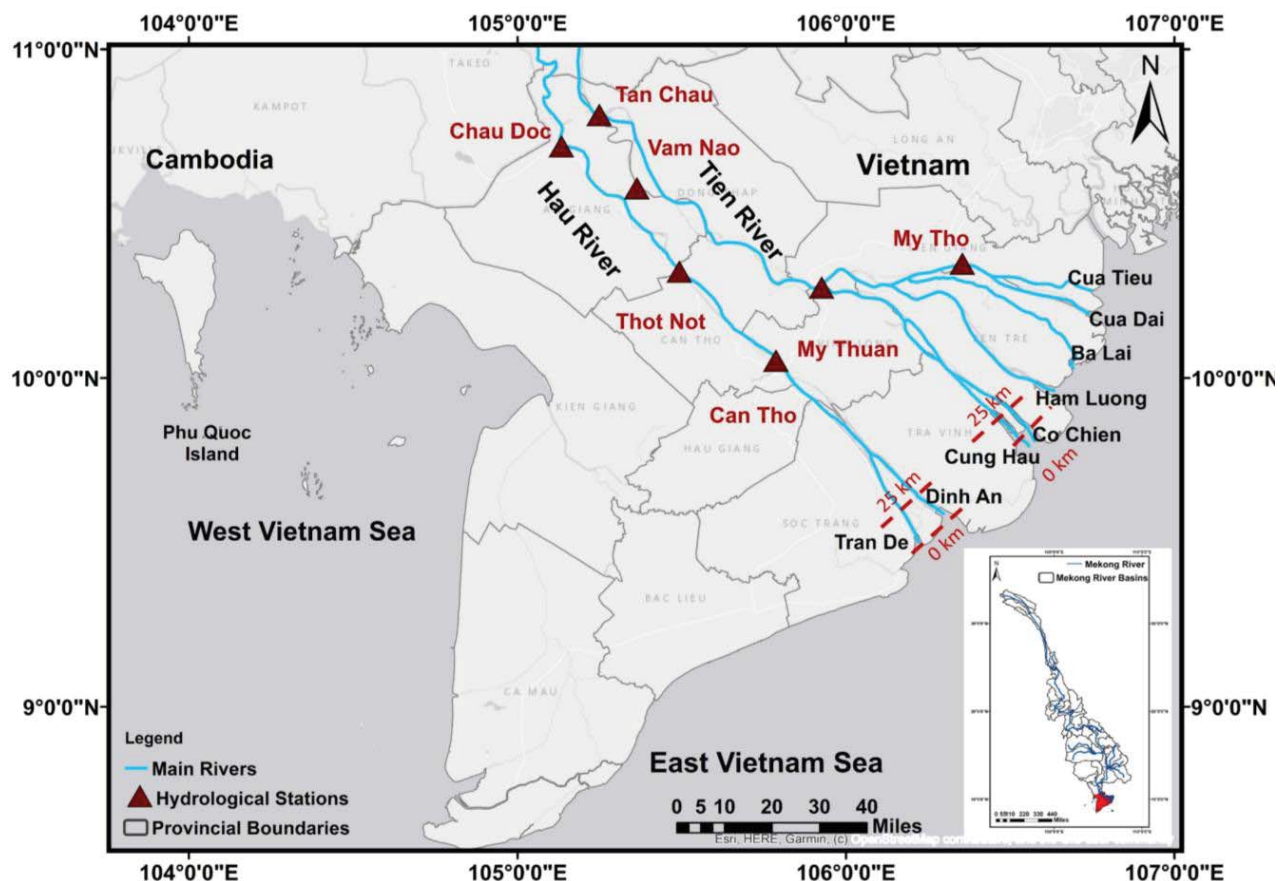


Fig. 1. The Vietnamese Mekong Delta's main rivers and hydrological stations.

3. Materials & methods

3.1. Numerical model configuration and estuarine parameter space analysis

To classify estuarine circulation, we utilized the estuarine parameter space, defined by the freshwater Froude number F_{rf} and the mixing number M , expressed as follows (Geyer & MacCready, 2014):

$$F_{\text{rf}} = \frac{U_{\text{R}}}{(\beta g s_{\text{ocean}} H)^{0.5}} \quad (1)$$

$$M^2 = \frac{C_{\text{D}} U_{\text{T}}^2}{\omega N_{\text{o}} H^2} \quad (2)$$

where $U_{\text{R}} = V/A$ is the cross-sectionally averaged river discharge velocity (m/s), V is the river volume flux (m^3/s), and A is the channel cross-sectional area (m^2). H is the cross-sectionally averaged depth (m). U_{T} is the amplitude of the cross-sectionally averaged tidal velocity (m/s). $N_{\text{o}} = (\beta g s_{\text{ocean}}/H)^{0.5}$ represents the buoyancy frequency for the maximum bottom-to-top salinity variation in an estuary (s^{-1}), $\beta = 7.7 \times 10^{-4}$ is the coefficient of haline contraction (psu^{-1}), s_{ocean} represents the ocean salinity = 35 (psu), and g is the gravitational acceleration = 9.8 (m/s^2). C_{D} is the drag coefficient = 2.5×10^{-3} (Figueroa et al., 2022), and ω is the tidal frequency = 1.4×10^{-4} (s^{-1}).

A one-dimensional hydrodynamic and advection-dispersion model (MIKE 11) was subsequently employed to estimate the estuarine parameter space. The model was calibrated using the hydrological and salinity concentration data of 2016 (Mai et al., 2018). The tidal ranges were assessed for every semidiurnal cycle throughout the dry season, and the spring and neap tides were defined based on higher high tides and lower low tides. In particular, we specified spring tides as those occurring around the full moon and new moon approximately every 14-15 days, while neap tides correspond to the first and third quarters of the moon, about 7 days after each spring tide. On the identified representative days, we estimated the relevant parameters (i.e., freshwater Froude number and mixing number) at 12-hour intervals, enabling us to track variations in estuarine circulation under different tidal conditions.

We acknowledge the limitations of using a 1D numerical model for assessing circulation dynamics; however, our study is not solely focused on short-term circulation variations driven by spring and neap tides but also aims to examine spatial variations in estuarine dynamics over the entire dry season. A 1D model is well-suited for capturing longitudinal salt transport and stratification, which are the key processes to investigate the interplay between estuarine circulation and morphological evolution in the VMD. Additionally, the limited availability of sufficient field data for calibrating 2D or 3D models presents a significant challenge, especially in large-scale riverine-estuarine systems such as the VMD. Thus, while higher dimensional modeling would provide more detailed insights into lateral circulation processes, the 1D approach remains a practical choice for evaluating the seasonal alterations and interactions between estuarine circulation and morphological variations in the delta.

3.2. Assessment of riverbed morphological evolution in the VMD

In our quest to examine the relevance between morphological changes and estuarine circulation, the 2017 and 2020 bathymetric datasets were used. The 2017 bathymetric data collection conducted in August and September of that year was facilitated by financial support from the Japan-ASEAN Science, Technology, and Innovation Platform (JASTIP) under Kyoto University's auspices (Binh et al., 2020). For the 2020 data, a comprehensive collection was undertaken across 2020 and 2021, produced by the Southern Institute of Water Resource Planning (SIWRP). The bathymetric data were interpolated by employing universal kriging, with the exponential method using the kernel function available in the Geostatistical Analyst module within ArcGIS 10 (Binh et al., 2020). Our subsequent analysis delved into annual mean morphological variations in terms of depth (m) and volume (m^3), for the 2017-2020 period. The Geomorphic Change Detection (GCD@6) tool within ArcGIS@10 was used to compute the annual disparities in riverbed elevations. We estimated the total annual riverbed incision and accretion volumes, the net volume of differences, and the net riverbed evolution depth for every 1 km segment along the two distributaries of the VMD.

3.3. Analyzing riverbank migration dynamics in the VMD

To identify bank erosion areas in our study, we followed the comprehensive methodology outlined in Quyen et al. (2023). We began by leveraging satellite data from the U.S. Geological Survey (USGS). We applied an atmospheric correction to ensure accurate subsequent analyses (Vanhellemont, 2019). Subsequently, to distinguish between water and non-water classes, we harnessed the capabilities of the Deep Forest (DF) model (Zhou & Feng, 2019; Cherif et al., 2022), generating binary maps. Furthermore, we finetuned the model's parameters to ensure optimal performance using the grid search cross-validation from the Scikit learn library (Pedregosa et al., 2011). Utilizing the ground truth pixels from 2021, we delineated regions of interest for both water and non-water classes and subsequently extracted the pixel value datasets for

deploying the DF model. Afterward, binary maps categorizing water and non-water classes were generated for the study sites across various years. The water boundaries were then transformed into vector format, i.e., polyline format, facilitating a more detailed analysis of temporal shoreline changes at the interval of 2017–2020. The Linear Regression Rate (LRR) was estimated as the average annual change in bank migration in meters.

4. Results & discussion

4.1. Influence of tidal cycles on estuarine circulation dynamics

The analysis revealed that the semidiurnal cycle significantly influenced the circulation patterns of estuaries throughout the dry season. In the Dinh An estuary, the circulation changed from a salt wedge estuary during spring tides to a strongly stratified estuary during neap tides (Fig. 2). In contrast, the Co Chien estuary exhibited a mixed pattern of salt wedge and strongly stratified circulation for both tidal phases, indicating less distinct variations in circulation dynamics (Fig. 2). In Dinh An, the transition in circulation patterns reflects the interaction between tidal forcing and river discharge in the dry season. During spring tides, stronger tidal forces strengthen landward salt transport, resulting in sharp halocline characteristics of the salt wedge (Wolanski et al., 1998). Conversely, during neap tides, weaker tidal forcing and relatively stronger river influence allow denser saltwater to intrude landward beneath the freshwater layer, maintaining a more stratified structure (Eslami et al., 2021). On the other hand, in Co Chien, the mixed circulation patterns elucidate that other factors beyond tidal forcing, particularly channel morphology, played a crucial role in shaping estuarine circulation (Fig. 3), leading to less distinguished shifts in circulation patterns between spring and neap tides (Eslami et al., 2021).

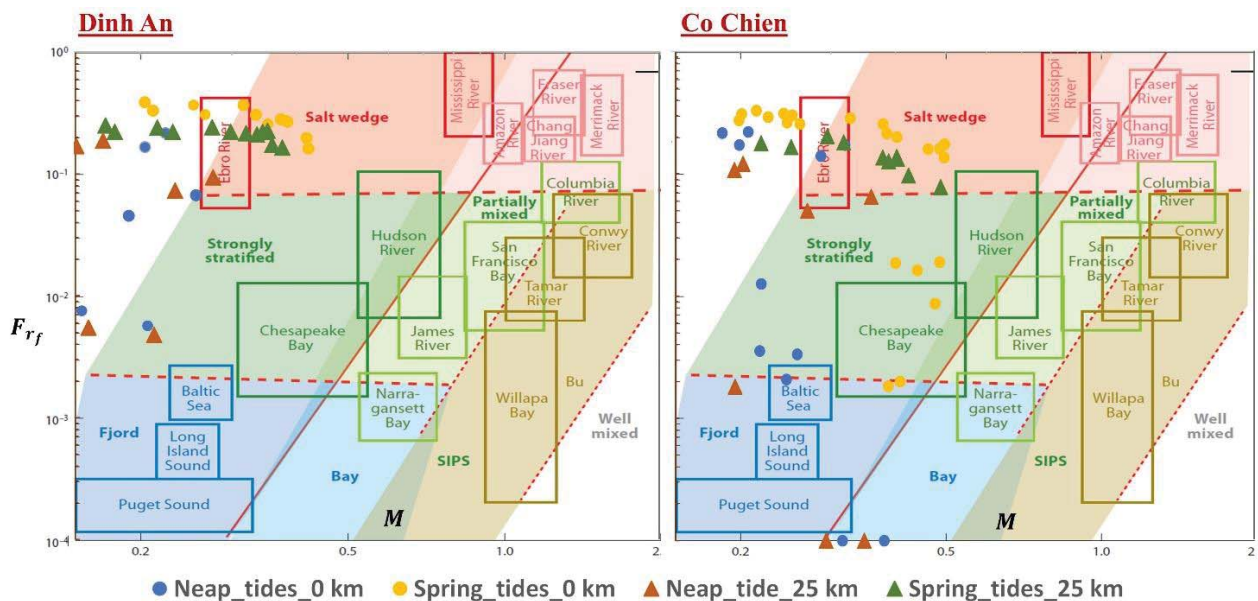


Fig. 2. The estuarine parameter space for Dinh An and Co Chien distributaries during the semidiurnal cycles of neap and spring tides at 0 km and 25 km from the river mouth.

4.2. Spatial variability in circulation and related morphological alterations

Spatially, the circulation dynamics at 0 km and 25 km from the river mouth displayed contrasting behaviors (Fig. 2). In Co Chien, circulation alternated between a salt wedge and strongly stratified conditions, predominantly influenced by severe morphological alterations in riverbed elevations (Ahmed et al., 2025). Contrarily, Dinh An maintained a relatively stable circulation pattern due to a more stabilized riverbed along its length (Fig. 3). These differences were attributed to substantial fluctuations in the cross-sectional average depth, directly impacting key hydrodynamic parameters, in particular, the mixing number and freshwater Froude number (Eq. 1,2), hence influencing the circulation regime. A deepened evolved riverbed generally enhances tidal penetration and reduces vertical mixing, promoting an unavoidable shift towards salt wedge and strongly stratified regimes. Conversely, uniform riverbed progression leads to consistent circulation patterns, although estuarine classification remained dependent on the balance between tidal forcing and river discharge. Specifically, the net riverbed evolution depth along Co Chien ranged between ± 2 m/year for every 1 km, with a net annual eroded volume of 1.5 Mm³/year. Meanwhile, the net riverbed evolution depth in Dinh An was relatively stable, typically ranging between ± 0.5 m/year every 1 km, with a net annual

deposited volume of 4.8 Mm³/year. This intensified rate of riverbed incisions is poised to increase the formation of scour holes, a direct consequence of significant bed alterations that entrap sediment within these depressions, thereby exacerbating riverbank erosion (Binh et al., 2022; Ahmed et al., 2024). These findings imply that circulation dynamics are more sensitive to morphological alterations in river systems with higher spring–neap variability compared to those that remain mixed or stratified over time (Eslami et al., 2021).

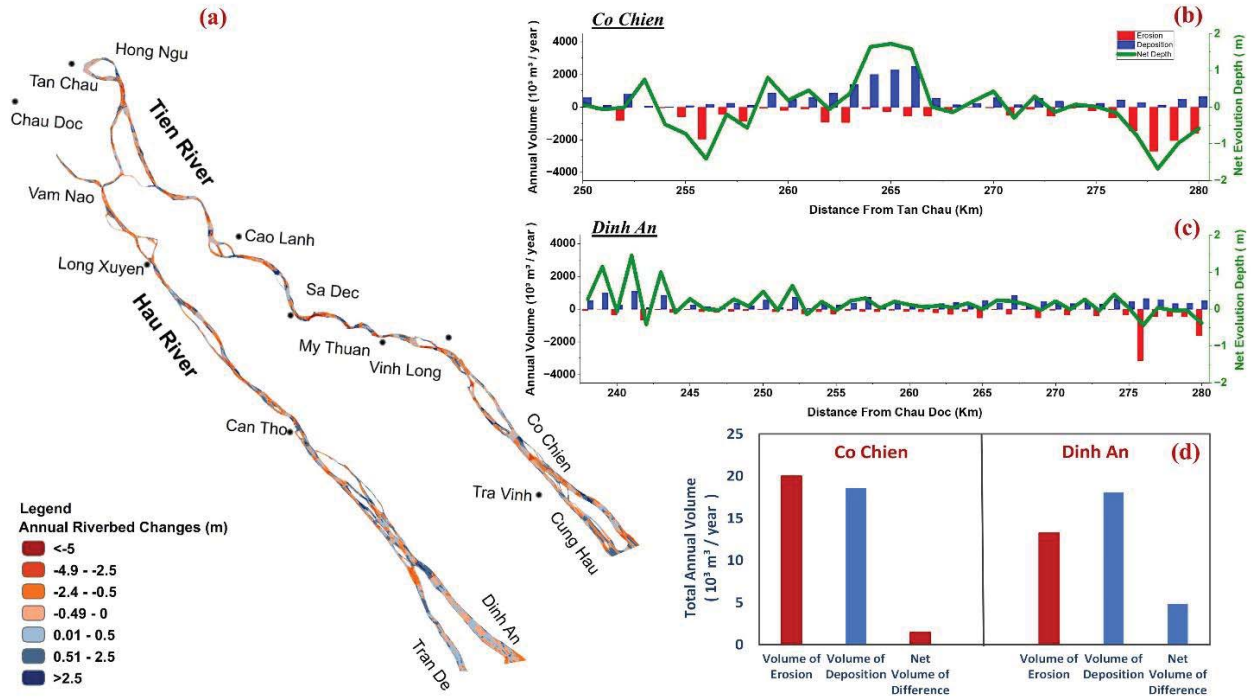


Fig. 3. (a) Analysis of annual morphological changes: annual DEM differences for 2017-2020; (b, c) annual evolution volume (10³ m³) and net annual evolution depth (m) for every 1 km long segment along Co Chien and Dinh An distributaries; (d) total annual volume of erosion, deposition, and net volume difference (10³ m³) for the respective distributaries.

4.3. Riverbank erosion and estuarine circulation interactions

The monthly variation analysis throughout the dry season unveiled that Dinh An was identified as a salt wedge estuary, whereas Co Chien was classified as a strongly stratified estuary (Fig. 4). Global studies have shown that salt wedge estuaries often tend to experience more localized riverbank erosion due to the discrete boundary between freshwater and saltwater (Ibàñez et al., 1996; Valle-Levinson, 2010). The movement of the salt wedge, where the SSC is substantially lower than that in the freshwater zone, can result in concentrated erosion along areas where the wedge interacts with riverbanks. On the contrary, strongly stratified estuaries characterized by high to moderate river flow velocities and low to moderate tidal velocities generally exhibit more widespread riverbank erosion because shear stresses act over a broader area (Valle-Levinson, 2010; Zhang et al., 2021), leading to more uniform erosion patterns along the riverbanks (Fig. 4). Our analysis of the annual riverbank migration rates from 2017 to 2020 supported this interrelation between estuarine circulation and erosion patterns, showing a confined riverbank erosion across different segments along Dinh An, with migration rates ranging between -0.5 and -5 m/year. Alternatively, Co Chien suffered an extensive riverbank migration across its length, with an approximate erosion rate of -5 m/year. Overall, these findings revealed that morphological changes have not only altered the salt flux regime of the estuary but have also contributed to developing a more complex system that requires more nuanced approaches for sediment management.

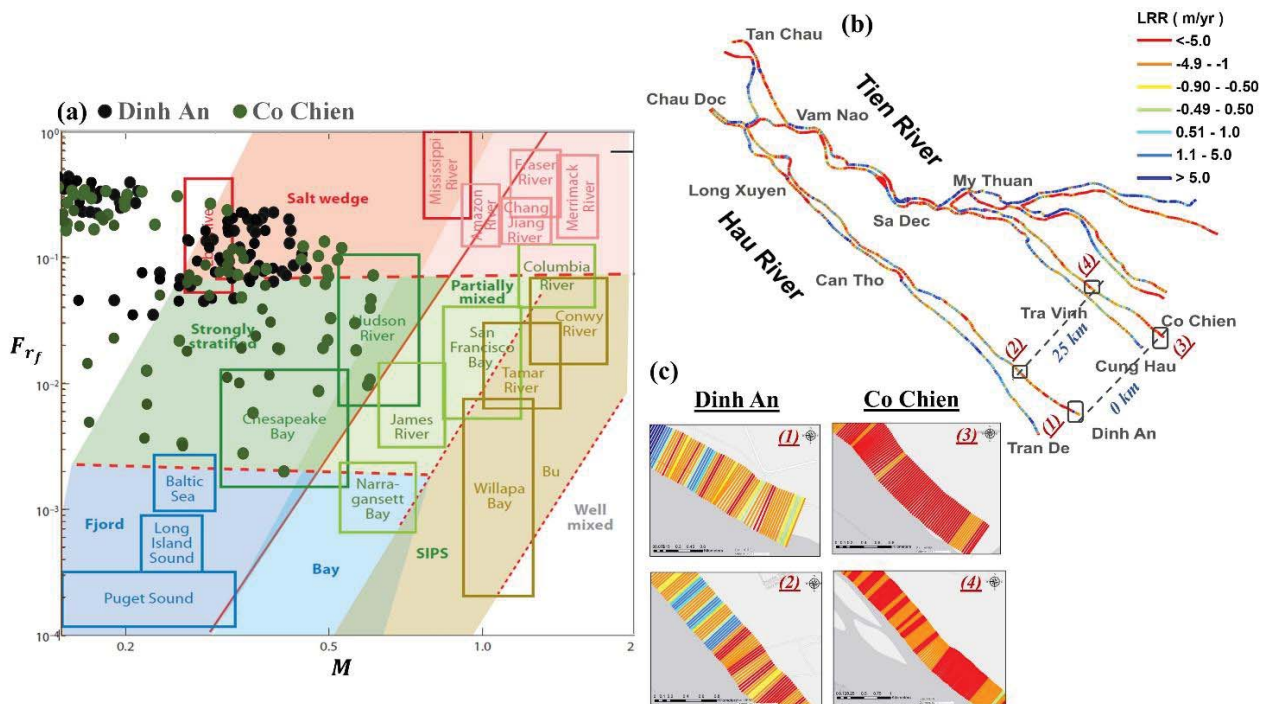


Fig. 4. (a) The estuarine parameter space for the Dinh An and Co Chien distributaries during the dry season of 2016, (b, c) the average annual riverbank migration rate (LRR) for 2017--2020 along the Co Chien and Dinh An distributaries. Panels 1, 2, 3, and 4 are typical segments of the riverbank migration rate at 0 km and 25 km from the river mouth for the respective distributaries.

5. Conclusion

The VMD boasts a vast and intricate river system, resulting in a complex relationship between circulation dynamics and morphological alterations. This study aims to shed light on this nuanced interrelationship. The analysis revealed that the semidiurnal tidal cycle significantly impacted the circulation patterns of estuaries across the delta. Spatially, circulation behavior varied between the two distributaries. In the Co Chien distributary, circulation alternated between salt wedge and strongly stratified conditions at 0 km and 25 km from the river mouth, respectively, driven by severe morphological alterations, with net riverbed evolution ranging between ± 2 m/year.

In contrast, the Dinh An distributary maintained a more stable circulation regime due to its relatively uniform riverbed, where the net riverbed evolution was typically ± 0.5 m/year. Additionally, during the dry season, Dinh An was classified as a salt wedge estuary, experiencing localized riverbank erosion, with migration rates ranging between -0.5 and -5 m/year, particularly near the wedge zones where the SSC was lower than that in the freshwater zones. Meanwhile, Co Chien, identified as a strongly stratified estuary, exhibited widespread riverbank erosion, averaging -5 m/year, caused by shear stresses acting across stratified water layers. This study improves our understanding of the complicated dynamics between circulation mechanisms and morphological evolution in the VMD. Given the escalating challenges from both natural and anthropogenic factors, these findings highlight the urgent need for integrated sediment management approaches to strengthen delta resilience and mitigate the impacts of ongoing morphological changes.

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