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Mechanisms of riverbank erosion on the Bassac river: Integrating field observations and stability analysis

T. K. TRAN[1] and T. A. DANG[2]*

[1]*Vietnam National University, Ho Chi Minh City,70000 Vietnam*

[2]*University of Science, VNU-HCM, 70000 Vietnam*

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***Corresponding author's email: dtan@hcmus.edu.vn**

सार – यह अध्ययन हाइड्रोडायनामिक, तलछट और आकारिकी (Morphology) विशेषताओं को एकीकृत करने के आधार पर वियतनामी मेकांग डेल्टा (VMD) के एन गियांग प्रांत के होआ लाक कम्यून में हौ बसाक नदी के किनारे नदी के किनारे के कटाव के कारणों की जांच करता है। नवंबर 2024 में एकत्र किए गए फील्ड डेटा, जो घटती बाढ़ के मौसम की स्थिति का प्रतिनिधित्व करते हैं, संकेत देते हैं कि उच्च प्रवाह वेग, विशेष रूप से मोड़ के बाहरी किनारों पर, अक्सर परिकलित अनुमेय गैर-अपघटनकारी वेगों (Calculated permissible non-eroding velocities) के करीब पहुंच गए या उससे अधिक हो गए। खड़ी ढलान (> 50 डिग्री), आसानी से नष्ट होने वाली जलोढ़ सामग्री, और ज्वारीय उतार-चढ़ाव अस्थिरता में और योगदान देते हैं। जबकि अपस्ट्रीम बांध और रेत खनन जैसे क्षेत्रीय कारक प्रणालीगत संवेदनशीलता को बढ़ाते हैं, हमारे निष्कर्ष स्थानीय संकेंद्रित प्रवाह ऊर्जा और भू-तकनीकी कमजोरियों की महत्वपूर्ण भूमिका को इंगित करते हैं। विश्लेषण एक बहु-चरणीय विफलता तंत्र (Multi-stage failure mechanism) को प्रकट करता है, जहां चरम बाढ़ के दौरान अत्यधिक वेग संभावित रूप से बेसल स्कोअर (Basal scour) के लिए प्राथमिक ट्रिगर के रूप में कार्य करते हैं, जबकि घटते मौसम के दौरान निरंतर, निकट-सीमा मान प्रवाह प्राकृतिक सुधार को रोकते हैं और नदी के किनारे की अस्थिरता को बनाए रखते हैं। यह अध्ययन कटाव तंत्र का एक महत्वपूर्ण स्नैपशॉट प्रदान करता है जो चरम बाढ़ की घटनाओं के दौरान तीव्र होने की संभावना है, स्थानीय शमन के लिए आवश्यक डेटा की पेशकश करता है और इस गतिशील नदी प्रणाली में निरंतर क्षेत्र-आधारित निगरानी की आवश्यकता पर बल देता है।

ABSTRACT. This study investigates the causes of riverbank erosion along the Hau Bassac River in Hoa Lac commune, An Giang province, Vietnamese Mekong Delta (VMD), based on integrating hydro-dynamic, sediment, and morphology characteristics. Field data collected in November 2024, representing receding flood season conditions, indicate that high flow velocities, especially on the outer banks of meanders, frequently approached or exceeded calculated permissible non-eroding velocities. Steep bank slopes (> 50 degrees), erodible alluvial materials, and tidal fluctu-ations further contribute to instability. While regional factors like upstream damming and sand mining exacerbate systemic vulnerability, our findings pinpoint the critical role of local concen-trated flow energy and geotechnical weaknesses. The analysis reveals a multi-stage failure mechanism, where extreme velocities during peak floods likely act as the primary trigger for basal scour, while sustained, near-threshold flows during the receding season prevent natural recovery and perpetuate bank instability. This study provides a critical snapshot of erosion mechanisms that are likely intensified during peak flood events, offering essential data for local mitigation and emphasizing the need for continued field-based monitoring in this dynamic river system.

Key words – Riverbank erosion, Water level fluctuation, Suspended sediment, Sand mining, Anthropogenic pressures.

1. Introduction

River deltas, as critical transitional zones between terrestrial and marine environments, are fundamentally shaped by the fluvial processes that deliver water and sediment (Hackney *et al*., 2020; Best, 2019). Sediments transported by rivers are the primary building blocks that sustain deltaic landforms, counteracting natural subsidence and maintaining coastal resilience (Dang *et al*., 2018; Kondolf *et al*., 2014). However, globally, riverine sediment

loads have experienced significant reductions due to a confluence of factors, including climate change-induced alterations in hydrological regimes and extensive anthropogenic activities such as dam construction, large-scale sand mining, and pervasive urbanization (Hackney *et al*., 2020). These widespread alterations to sediment dynamics precipitate detrimental impacts on deltaic systems, including accelerated landform degradation, compromised aquatic ecosystems, and increased salinity intrusion (Kondolf *et al*., 2014). The VMD, one of the world's largest and most socio-economically vital deltaic regions, serves as a prominent example of a system acutely vulnerable to these mounting pressures (Boretti, 2020; Lee & Dang, 2020).

The hydrological regime of the Mekong River, a dominant control on VMD's geomorphology and ecology, has been substantially altered by extensive upstream water resource development, particularly the construction of numerous hydropower dams (Hecht *et al*., 2019). These structures have significantly reduced the suspended sediment concentration (SSC) reaching the delta, with studies indicating decreases of 50–94% in the lower Mekong due to dams in the Lancang cascade alone (Kondolf *et al*., 2014). The cumulative impact of all dams in the basin has been estimated to cause a 74% SSC reduction in the VMD (Binh *et al*., 2020b). This drastic reduction in sediment input is further exacerbated by intensive in-channel sand mining within the VMD itself, which has accelerated from approximately 7.75 Mm^3/yr in 2012 to potentially exceeding 42 Mm^3/yr in recent years when accounting for illegal extraction (Kantoush et al., 2017). The combined effects of sediment starvation from upstream and local over-extraction have led to severe morphological degradation, including riverbed incision, and a notable increase in the frequency and intensity of riverbank erosion and associated instability (Anthony *et al*., 2015, Binh *et al*., 2020c). Consequently, riverbank erosion now poses a significant threat to communities, agricultural land, and infrastructure throughout the VMD (Nguyen, 2018; Rahman & Gain, 2020).

Understanding the precise mechanisms driving riverbank erosion in specific reaches of the VMD is crucial for developing effective mitigation solutions. While regional trends of sediment reduction are well-documented, the local manifestation of erosion is governed by a complex interplay of site-specific factors. These include local hydrodynamics, channel geomorphology, geotechnical properties of bank materials, and tidal influences (Dragićević *et al*., 2017; Duong & Do, 2019). However, detailed field-based investigations into these local controlling factors, particularly in areas experiencing acute erosion like Hoa Lac commune in An Giang province, remain limited. This study aims to fill this gap by providing a granular, field-based assessment of the proximate causes of erosion at a vulnerable, landslide-prone location.

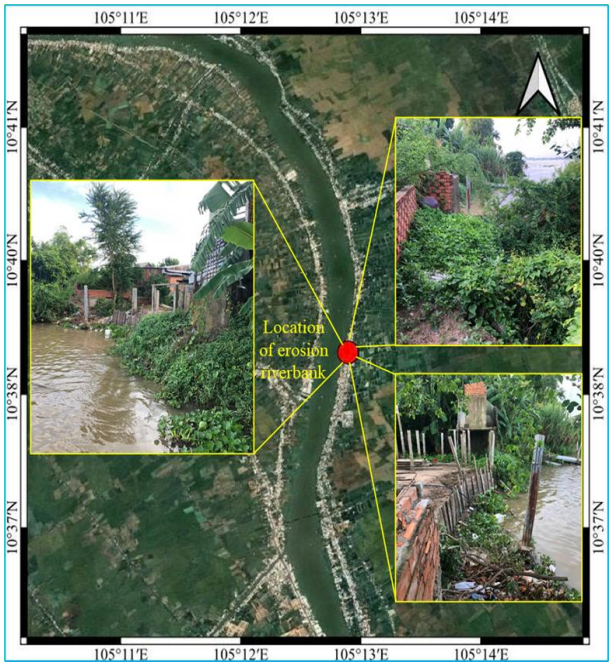


Fig. 1. Map of the study area with location of eroded riverbank on September 23, 2024, in Hoa Loc and Hoa Hung 1 hamlets, Hoa Lac commune, a landslide occurred on the bank of the Bassac River (Source: Google Earth)

2. Data and methodology

2.1. *Study area description*

The study was conducted along a segment of the Bassac River traversing Hoa Lac commune, Phu Tan district, An Giang province, situated within the upper floodplain of the VMD (Fig. 1). The Hau River, a principal distributary of the Mekong, is a vital water resource for the region. The area is characterized by densely populated riverbanks and intensive agriculture, making local communities highly vulnerable to land loss from riverbank erosion. A significant landslide event on September 23, 2024, at the location corresponding to our cross-section CS3, impacted several households and underscored the urgency of this research. The river reach is influenced by both the seasonal flood pulse of the Mekong and diurnal tidal effects, creating a complex hydrodynamic environment.

2.2. *Field data collection and analysis*

A comprehensive field data collection campaign was undertaken in November, 2024, to characterize the

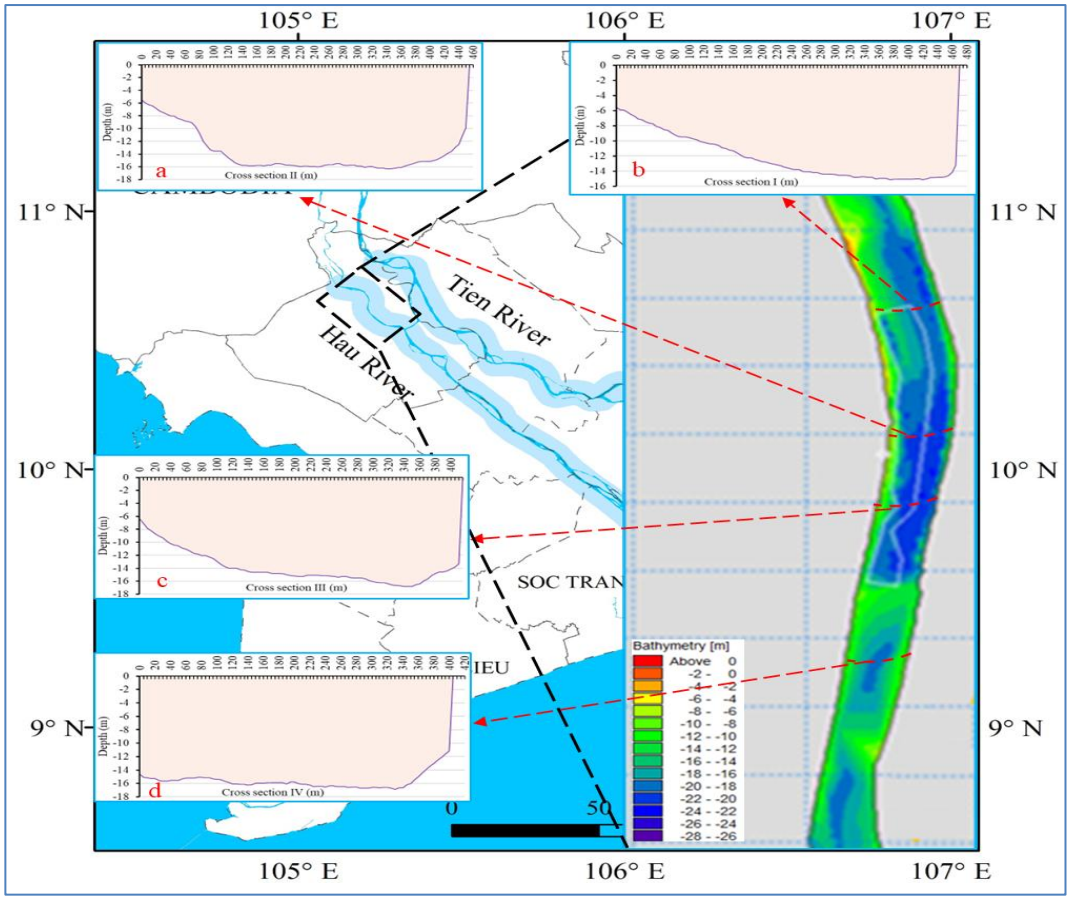


Fig. 2. Cross-sectional morphology at representative river-sections of the eroded Bassac River

geomorphological, hydrodynamic, and sedimentological conditions of the study reach, particularly in areas exhibiting active erosion. This timing was strategically chosen to capture post-peak flow conditions during the annual receding flood season, a period known to be associated with significant bank instability due to rapid water level changes and still-elevated discharges.

2.2.1. *Geomorphological features survey*

Detailed river cross-sections were surveyed at locations representative of both eroded and relatively stable bank sections. Bathymetric data were acquired using a single-beam echosounder integrated with a Differential Global Positioning System (DGPS) to ensure high-accuracy horizontal and vertical positioning (Langat *et al*., 2019; Hemmelder *et al*., 2018). These surveys provided data for constructing detailed cross-sectional profiles and characterizing the riverbed morphology. Bank slope angles at the erosion sites were measured using clinometers and topographic survey techniques. Visual observations and photographic documentation of bank features, including signs of instability (*e.g*., tension cracks, slumping, undercutting), soil stratigraphy (where exposed), and riparian vegetation cover, were systematically recorded.

2.2.2. *Hydrodynamics features survey*

Flow velocity profiles and flow discharge were measured at selected transects corresponding to the bathymetric survey lines using an Acoustic Doppler Current Profiler (ADCP). The ADCP was deployed from a boat, traversing the river to obtain detailed information on the distribution of two-dimensional flow structure, particularly focusing on near-bank velocities and secondary current patterns that could contribute to erosion. In addition, water level and flow disharge data were obtained during the survey period from the Chau Doc gauging station located upstream to understand flow disharge distribution and tidal propagation features.

2.2.3. *Sediment and meterials samples collection*

Suspended sediment concentration and bed material samples were collected from the multiple points along the surveyed cross-sections using Rinko Profiler tool and a Van Veen grab sampler. These samples were subsequently

analyzed in the laboratory for particle size distribution using standard sieving and hydrometer methods to determine the median grain size (d_{50}) and overall textural composition. The d_{50} values obtained were critical inputs for calculating the permissible non-eroding velocity.

2.3. *Cacultion of riverbank stability and erosion risks*

2.3.1. *Calculation of non-eroding velocity*

The primary method for assessing erosion potential involved calculating the permissible non-eroding velocity (Vn) for riverbed material using the Neill (1967) formula (Equation 1). This formula was selected for its robustness in estimating threshold velocities for non-cohesive sediments. However, it is important to acknowledge its inherent assumptions, such as uniform sediment properties and the empirical nature of the coefficient C. The presence of cohesive sediment layers, which may exist within the alluvial stratigraphy, could locally increase the erosion threshold. Therefore, the calculated Vn values should be interpreted as a conservative estimate of the bank material's resistance to erosion.

This formula considers the d_{50}, water depth (h), and C is Coefficient, usually taken as a value of about 1.58 and s is specific gravity of sand particles:

$$v_n = C * \left(\frac{h}{d_{50}}\right)^{1/6} \sqrt{g(s-1) * d_{50}} \quad (1)$$

2.3.2. *Qualitative assessment of bank stability*

In addition to the quantitative velocity comparison, a qualitative assessment of bank stability was conducted by integrating observations of bank geometry (height and slope angle), visible signs of erosion and mass wasting (undercutting, tension cracks, slumps), riverbank material composition (based on visual inspection and available geological information), riparian vegetation cover and type (Hamshaw *et al*., 2017; Langat *et al*., 2019) and proximity to potential anthropogenic disturbances. This holistic approach allowed for an interpretation of the dominant erosion processes and an assessment of the relative stability of different bank segments within the study area (Duong and Do, 2019; Das *et al*., 2014).

3. Results and discussion

This section presents the primary findings from the field investigations conducted in Phu Tan district, An Giang province, focusing on the hydrodynamic conditions, river morphology, and sediment characteristics pertinent to riverbank erosion along the Hau Bassac River. The results are discussed in the context of established geomorphological principles and relevant literature to elucidate the dominant erosion mechanisms and contributing factors.

3.1. *Observed riverbank erosion characteristics*

Field surveys conducted on November 25, 2024, particularly in the aftermath of the landslide in Hoa Lac commune (Fig.1), confirmed active and significant riverbank erosion within the study reach. Visual evidence included fresh scarps, slumped bank material, and undercutting at the toe of the banks.

3.1.1. *River morphology and bank geometry*

The investigated segment of the Hau Bassac River exhibits distinct meandering characteristics, particularly in the vicinity of the observed erosion sites (conceptualized as CS1 to CS4). Cross-sectional surveys (Fig. 2, showing representative morphology) revealed that erosion was most pronounced along the outer bends of these meanders. At these locations, the riverbanks were notably steep, with measured slope angles ranging from 45 to 78 degrees. The riverbed adjacent to these eroding outer banks was characterized by significant depths, varying from -12 m to -14 m relative to the local water surface datum during the survey. This combination of steep bank slopes and deep near-riverbank is indicative of active erosional processes, including basal scour and undercutting, which predispose the banks to gravitational failure (Duong and Do, 2019). In contrast, inner bend areas typically exhibited gentler slopes and shallower depths, consistent with depositional environments.

3.1.2. *Hydrodynamic conditions*

ADCP measurements provided detailed insights into the flow dynamics within the study reach (Figs. 3a-d, illustrating velocity distributions at cross-sections I-IV). A consistent pattern observed was the concentration of higher flow velocities towards the outer banks of meanders, directly impinging on the eroding sections. Near-bank velocities on the eroding (left) bank were consistently higher than those on the more stable (right or inner) bank. For example, while velocities on the inner bank might be below 0.375 m/s, velocities approaching or exceeding 0.5 m/s were recorded near the toe of the eroding outer banks during the survey period. The flow direction was often observed to be oblique to the bank line at these erosion hotspots, particularly during high discharge, further enhancing the erosive stress on the bank material (Fig. 4). The influence of tides was also apparent from water level fluctuations observed during the field

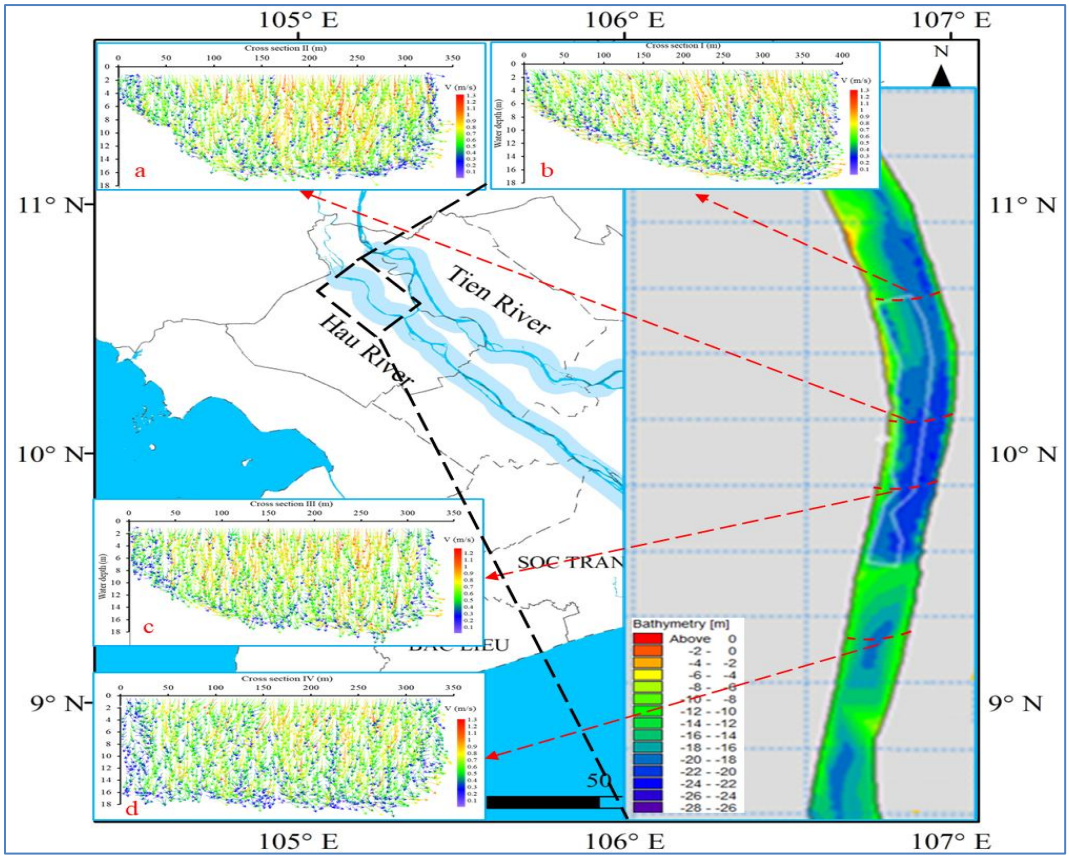


Fig. 3. Surveyed data of distribution of flow velocity fields using ADCP device at a) cross section 1 (CS1), b) cross section 2 (CS2), c) cross section 3 (CS3) and d) cross section 4 (CS4) belongings to the Bassac River section

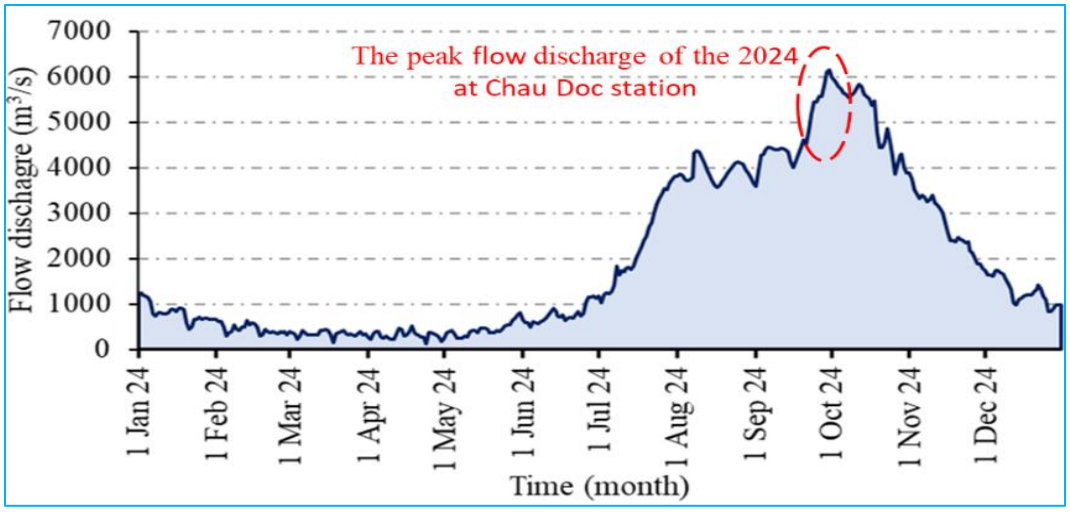


Fig. 4. Distribution of flow dischagre across cross section of Bassac River at Chau Doc hydrology station during the flooding season months in 2024

campaign and from historical data at the Chau Doc station (Fig. 5, showing high tide range in 2024).

The significant diurnal tidal range, especially when superimposed on high seasonal flood levels (Table 1), contributes to cyclic changes in bank saturation and pore water pressure. Such fluctuations are known to reduce the shear strength of alluvial bank materials and can trigger instability, particularly during rapid water level drawdown (Allison *et al*., 2017).

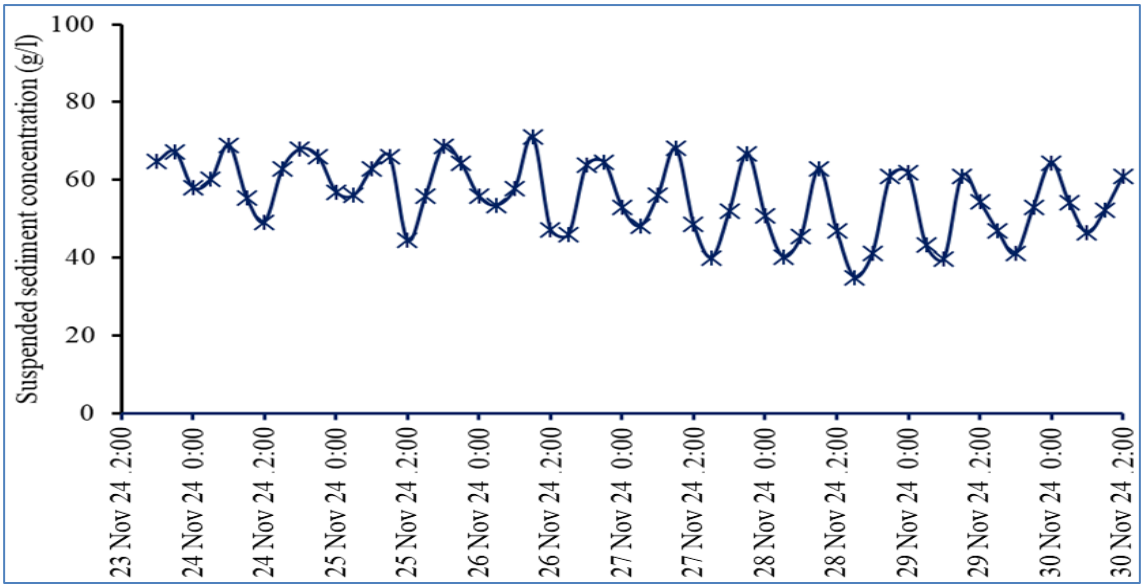


Fig. 5. Distribution of suspended sediment concentration serveyed near eroded riverbank

TABLE 1

Temporal distribution of water level and flow discharge at Chau Doc station during flood peak period in 2024

Time	Water level (mm)	Flow discharge (m^3/s)	Time	Water level (mm)	Flow discharge (m^3/s)
15 Sep 2024	193	4140	01-Oct-24	277	5980
16 Sep 2024	201	4000	02-Oct-24	279	5970
17 Sep 2024	214	4160	03-Oct-24	282	5880
18 Sep 2024	228	4300	04-Oct-24	287	5780
19 Sep 2024	238	4440	05-Oct-24	292	5740
20 Sep 2024	247	4610	06-Oct-24	293	5640
21 Sep 2024	254	4530	07-Oct-24	289	5620
22 Sep 2024	259	4810	08-Oct-24	288	5550
23 Sep 2024	262	5170	09-Oct-24	284	5600
24 Sep 2024	263	5440	10-Oct-24	279	5650
25 Sep 2024	264	5450	11-Oct-24	277	5730
26 Sep 2024	267	5580	12-Oct-24	275	5830
27 Sep 2024	272	5580	13-Oct-24	273	5800
28 Sep 2024	275	5820	14-Oct-24	270	5630
29 Sep 2024	277	6100	15-Oct-24	270	5580

3.1.3. *Suspended sediment concentration and bed material characteristics*

Bed material samples collected from the study reach consisted primarily of fine to medium sands and silts, with d_{50} values ranging from 0.08 mm to 0.36 mm. These materials are relatively erodible under moderate to high flow velocities. Visual inspection of exposed bank sections revealed a stratigraphy typical of alluvial deposits in the VMD, often comprising layers of silts, clays, and fine sands, with varying degrees of cohesion (Brunier *et al*., 2014). The presence of less cohesive sandy layers at or near the bank toe can make the banks particularly vulnerable to undercutting and subsequent cantilever failure (Das *et al*., 2014). Riparian vegetation along the actively eroding sections was often sparse or absent, reducing the natural protection afforded by root systems (Thakur *et al*., 2012).

TABLE 2

Calculate results of non-eroding velocity at cross sections

Features	CS1	CS2	CS3	CS4
dmax (mm)	0.19	0.40	0.47	0.58
d_{50} (mm)	0.08	0.17	0.23	0.36
h (m)	11.2	14.0	14.3	12.5
Vn (m/s)	0.41	0.52	0.58	0.67
$V_{measured}$ (m/s)	0.49	0.57	0.68	0.61

3.2. *Assessment of erosion risks using permissible velocity*

The calculated non-eroding velocities (vn) for the study reach, based on the Neill formula (1967) (Equation 1) and bed materials and water depth is given in Table 2. A comparison of these vn values with the measured flow velocities at specific locations revealed critical insights into the erosion potential.

In actively eroding sections (*e.g.*, CS3 to CS4), particularly along the outer bends, the measured near-bank velocities during the November 2024 survey frequently approached or exceeded the upper limit of the calculated vn range. This indicates that the prevailing flow conditions even during the receding flood season were sufficient to entrain bed material and cause erosion at the bank toe, leading to undercutting and bank instability. At other surveyed locations, typically on inner bends or straighter reaches, measured near-bank velocities were often below the vn range, suggesting a lower intrinsic potential for erosion under the specific conditions of the survey.

It is crucial to note that these comparisons are based on data collected during the receding flood. During the peak flood season (September-October, Table 1), when flow discharges and water levels are significantly higher, flow velocities across wider areas of the channel are expected to be substantially greater. Under such peak conditions, the data indicate that even during the receding flood season, flow velocities were sufficient to cause erosion, suggesting that the erosive potential during peak flood conditions is likely significantly greater (Dragićević *et al*., 2017; Binh *et al*., 2020a).

3.3. *Discussions*

3.3.1. *Contributing factors*

The findings from this field-based investigation highlight that riverbank erosion in Phu Tan district is a multifaceted problem driven by a combination of natural fluvial geomorphic processes and likely exacerbated by regional anthropogenic pressures. The inherent meandering nature of the Bassac River in this reach is a primary geomorphic control, predisposing outer banks to erosion due to higher shear stresses and secondary currents (Thorne, 1982). The seasonal flood pulse of the Mekong delivers the high energy required for significant morphological work (Lauri *et al*., 2012). Tidal fluctuations further contribute to bank weakening through saturation-desiccation cycles and pore pressure changes, particularly in the fine-grained alluvial bank materials (Hackney *et al*., 2020). The erodibility of the local bank sediments (fine sands and silts) means that even moderate exceedances of the permissible velocity, such as those observed during the receding flood, can lead to significant material removal over time.

3.3.2. *Anthropogenic influences*

Sediment deficit: The well-documented reduction in suspended sediment load throughout the Mekong Delta due to upstream damming (Kondolf *et al*., 2014; Binh *et al*., 2020b; Xue *et al*., 2011; Hung et al., 2014) creates "sediment-hungry" water. This sediment-starved flow has an increased potential energy, enhancing its capacity to erode its bed and banks as it seeks to regain its sediment carrying capacity. While this study did not include a direct comparison with historical bathymetry, the observed deep channels (-12 m to -14 m) along the outer bends are consistent with the patterns of riverbed incision reported in other studies of the VMD (*e.g.*, Brunier *et al*., 2014; Hackney *et al*., 2020), suggesting a potential local manifestation of this regional trend. This underlying condition makes the riverbanks systemically more vulnerable to erosion (Best, 2019).

Sand mining: Large-scale sand mining in the river and delta channels is a major and well-documented issue in the VMD. Local reports and broader studies (e.g., Gruel *et al*., 2022; Hackney *et al*., 2020) confirm that intensive extraction, both legal and illegal, is prevalent in many

reaches of the Hau River, including in An Giang province. Such activities are known to cause significant riverbed incision, alter local hydrodynamics, and directly destabilize riverbanks by removing basal support (Hackney *et al*., 2020; Brunier *et al*., 2014). The formation of scour holes can further concentrate erosive flows and trigger bank failures, undoubtedly exacerbating the observed erosion if occurring within the influence zone of the study area (Nguyen, 2018).

Other Anthropogenic pressures: Human activities such as alterations to riparian vegetation for agriculture or infrastructure development can reduce bank strength and increase susceptibility to erosion (Thakur *et al*., 2012; Langat *et al*., 2019).

3.3.3. *Erosion Mechanisms at Critical Cross-Sections: A Deeper Analysis*

The quantitative data presented in Table 2 provide a compelling insight into the erosional dynamics of the study reach. The case of cross-section CS3, the site of the September 2024 landslide, is particularly illustrative. Here, the measured near-bank velocity during our survey ($V_{measured}$ = 0.68 m/s) significantly exceeded the calculated non-eroding threshold (V_n = 0.58 m/s). This finding directly confirms that erosive conditions were prevalent even during the receding flood season. A deeper analysis reveals a multi-stage failure mechanism:

The role of peak flood as a triggering mechanism: The landslide occurred in late September, coinciding with the peak flood period when discharges exceeded 6,000 m^3/s (Table 1, Fig. 4). Flow velocities during this peak would have been substantially higher than the 0.68 m/s measured in November, decisively exceeding the non-eroding threshold. This peak flow event likely acted as the primary triggering factor, causing intense basal scour that severely undercut the bank toe and initiated critical instability. Even with the conservative nature of the Neill formula, it is almost certain that peak flood velocities would have overwhelmed the bank's material resistance.

Geotechnical instability during flood recession: The survey in November captured the "aftermath" conditions. The rapid drawdown of water levels from the flood peak weakens bank stability by increasing pore water pressure within the bank materials, which reduces the soil's effective stress and shear strength. In combination with the steep bank slopes (45-78 degrees) and the pre-existing undercut from the peak flood, this created the perfect conditions for a geotechnical failure, where the over-steepened bank collapsed under its own weight.

Sustaining erosional pressure from receding flows: The high velocity (0.68 m/s) observed during the receding flood, while not the primary trigger for the initial collapse, plays a crucial role as a sustaining factor. It generates sufficient energy to prevent the deposition of a protective sediment layer at the bank toe and continuously removes slumped material from the failure. This process inhibits any natural recovery, keeps the bank toe exposed, and maintains the bank in a perpetually vulnerable and actively eroding state.

Therefore, the erosion at CS3 is not the result of a single process but a cascade of events: the river's meandering nature and systemic sediment deficit create a pre-conditioned vulnerability; peak flood flows provide the hydrodynamic trigger for basal scour; and the combination of geotechnical weaknesses during flood recession and sustained erosive flows culminates in catastrophic and ongoing failure. This multi-faceted mechanism underscores that effective mitigation must address not only hydrodynamic forces but also the geotechnical properties of the riverbanks.

3.3.4. *Limitations and recommendations for further research*

The primary limitation of this study, as highlighted for proper context throughout this paper, is that the direct field measurements represent a "snapshot" in time (November 25, 2024), corresponding to the receding flood season. While these data are valuable for identifying key erosion mechanisms, riverbank erosion is a dynamic process that varies significantly with seasonal changes in discharge and water level. To gain a more comprehensive understanding of the annual erosion cycle and the impact of peak flood events, further research should include:

Long-term monitoring: Continuous or at least more frequent measurements of flow velocities, water levels, and bank profiles, especially during different phases of the flood hydrograph (rising limb, peak, falling limb) and during both dry and wet seasons (Das *et al*., 2014; Binh *et al*., 2020c).

Detailed geotechnical investigations: In-situ and laboratory testing of bank material properties (e.g., shear strength, cohesion, particle size distribution of different layers) would provide more accurate parameters for stability analyses beyond empirical velocity calculations (Duong and Do, 2019).

Assessment of local anthropogenic impacts: A detailed survey of local activities such as sand extraction (if any), boat traffic patterns, and land use changes along the riverbanks in Phu Tan district would help to quantify their

specific contribution to the observed erosion (Tu *et al*., 2021; Hamshaw *et al*., 2017; Hemmelder *et al*., 2018).

The abstract's reference to future scour hole formation and net incision volumes under different sediment reduction scenarios suggests that a broader research program, potentially incorporating numerical modeling (though excluded from the detailed methodology of this specific paper), is underway or planned. Integrating findings from such local, field-based studies with larger-scale regional models is crucial for a holistic understanding and effective management of riverbank erosion in the VMD (Duc *et al*., 2020; Kantoush *et al*., 2017).

4. Conclusions

This field-based investigation in Hoa Lac commune concludes that riverbank erosion along the Hau Bassac River is primarily driven by concentrated hydrodynamic forces on meandering outer bends, where flow velocities frequently exceed calculated permissible non-eroding thresholds, even under receding flood season conditions. Steep bank slopes, erodible alluvial sediments, and tidal fluctuations significantly contribute to this instability.

The observed erosion occurs within a regional context of diminished sediment supply and potential in-river sand mining, which increase the river's intrinsic erosive capacity. Our findings highlight a critical multi-stage failure mechanism where peak flood events likely trigger initial instability through intense basal scour, followed by geotechnical failure and sustained erosion during the receding flood phase. The data strongly suggest that peak flood events exert even greater erosive stress, accelerating erosion significantly. Therefore, integrated management solutions addressing both local geomorphic conditions and basin-scale anthropogenic impacts are essential for mitigating riverbank erosion and ensuring the sustainability of this vital river segment.

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Authors’ Contributions

T. A. DANG: Investigation; calculating and checking results; writing-review and editing draft.

T. K. TRAN: Conceptualization; methodology; data analysis and writing-original draft preparation. (*email:* ttkim@hcmus.edu.vn).

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