

The effect of lateral bank erosion on the mangrove channel of Langkawi Island, Malaysia

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Abstract. Hashim SS, Abd Aziz KN, Tajam J, Mohd FA, Roslani MA, Kamaruddin SA, Latif ZA, Maulud KNA, Ahmad A, Azahary WAHWM. 2025. The effect of lateral bank erosion on the mangrove channel of Langkawi Island, Malaysia. *Asian J For* 9: 97-107. Mangrove forests, essential marine ecosystems that support marine life and economic activities, face threats from natural factors like monsoon seasons and artificial threats of human interventions. The extent of mangroves in channels depends on the hydrological properties of lateral erosion, necessitating a thorough assessment for conservation. This study utilizes erosion pins to observe lateral bank erosion in two different scenes of mangrove channels within Langkawi Island; the pristine (Selat Tuba) and the eventful channel (Sg. Kilim). Findings reveal varying erosion rates (0.03-0.62 m/year) in Sg. Kilim due to monsoon seasons and human activity influences, while Selat Tuba remains stable throughout the monsoon seasons with a ratio of 2.7:1. The study categorizes eroded banks into four distinct types based on erosion patterns across the upper, middle, and lower sections. The spatial differences in erosion types that influence the bank's conditions emphasize the need for tailored conservation approaches. Statistical analyses highlight significant variations in lateral erosion rates in Sg. Kilim underscores the impact of uncontrolled tourism activities. Sustainable management efforts should be prioritized to mitigate lateral erosion, especially in Selat Tuba, where human activities may exacerbate the issue in the future. This research provides valuable insights for coastal resource management, emphasizing the crucial role of maintaining mangrove channel bank stability.

Keywords: Anthropogenic impact, Langkawi, lateral bank erosion, mangrove channel, mangrove forest, monsoon season

INTRODUCTION

Mangrove ecosystems, characterized by a unique blend of terrestrials and marine, are home to numerous marine species and contribute billions of dollars worth of marine products and services to protect coastlines (Khan et al. 2024). Services presented by mangroves include protection from waves and storms, nursery grounds for various sea organisms, and carbon stocks in coastal regions. The mangrove channels of Langkawi Island are a study area that has many-faceted bio-diversity characteristics and a complex ecological environment. Lateral erosion of banks can dramatically modify the physical and biological features of mangrove channels. These roots help hold certain kinds of soil; nonetheless, in case of erosion, the functional structures of mangrove trees disappear and contribute to further coastline erosion (Islam et al. 2024). Some channels may develop within the mangrove areas and are important to the survival of mangrove forests as they are dietary and sediment-based, besides acting as means of transport (McLachlan et al. 2020). Stabilized tidal channels

are as useful as stabilized coastal areas, and previous studies proved that mangrove ecosystems are very useful in preventing coastal erosion (Besset et al. 2019; Brunier et al. 2019). Nonetheless, the impact of lateral bank erosion inside and outside the mangrove channels has not been well studied in detail. This also becomes a concern because mangrove channels are anticipated to undergo SLR incidences. These ecosystems are also under numerous natural and anthropogenic pressures, especially lateral bank erosion. Consequently, mangrove ecosystems are increasingly degraded through various anthropogenic activities in areas like urbanization and deforestation, affecting their ability to perform these functions and the human communities that depend on them (Yahaya et al. 2024).

Researchers have noted that high sediment trapped on the mangrove system from upstream erosion reduces light penetration, which is important for the healthy growth of mangroves and affects water quality. Climate change and human-imposed change have led to lateral bank erosion and mangrove alterations. Therefore, understanding the

mechanisms of mangrove erosion will be critical in determining the ability or otherwise of the mangrove ecosystem to withstand future climate change (Kamlun et al. 2024; Roslani 2024; Sahari et al. 2024; Wong et al. 2024). Lateral erosion in mangrove channels can be defined as the slow process of losing the channel edges, and this plays an important role in local geomorphology since erosions are crucial in defining the channel (Li et al. 2021). This gentle but irresistible force of erosion can become the leading parameter by which the health and survivability of the mangrove channels will stand against these challenges. However, such erosions can, in one way or another, be classified as risky if, for instance, it advances the position of land and ecosystems. In this regard, the mangrove area, including the channels surrounding it over the past decades, has also been another commercial center like the tourism sector sustaining a country's focal economic factor and stability (Spalding and Parrett 2019).

Bank erosion may be measured at different temporal frequencies, spatial resolutions, and accuracies that will aid in evaluating and quantifying the different phases of the erosion cycle in lateral bank profiles. Essential documentation of mass failure events can go a long way in determining the comparative relative bank erosion process and evaluation of volume loss (Duró et al. 2018). Relative to this, the erosion pins might prove helpful in measuring the bank erosion processes over vast distances and provide an accurate and reliable method that could be applied in the vegetated mangrove channel (Myers et al. 2019). In this way, the study wants to provide specific findings that are valuable beyond academia and could help interest managers, scientists, and tourism authorities on-site. Therefore, this study sought to establish lateral bank erosion rates and analyze river channels' temporal and spatial variability in mangroves, as well as different monsoon seasons and land use activities. Studying the channel morphology and lateral bank erosion in the coastal mangrove ecosystem of Langkawi Island has not only research importance and general appreciation of these unique ecosystems, but it is critical for the concomitant

social, economic, and cultural co-modalities that exist within such an environment.

MATERIALS AND METHODS

Study area

Langkawi is on the northern peninsula of Malaysia, and it is roughly 47,848.36 hectares in size. It is dominated by the climate of the Southeast Asia maritime continent monsoon (southwest monsoon and the northwest monsoon) that compromise of two indistinctive wet seasons (April to June with slight rain of 290 mm/month; July to October with heavy rainfall of 300mm/monthly) and one distinct dry season (November to March with mostly sunny and windy weather) (Mokhtar et al. 2019; Ayob et al. 2020). The marine ecosystem in Langkawi is influenced by the semi-diurnal tide of two high and two low tides of approximately equivalent height every lunar day (Din et al. 2017). Langkawi Island consists of six districts: Kuah, Ayer Hangat, Bohor, Kedawang, Padang Matsirat, and Ulu Melaka. Three primary islands are inhabited: Langkawi, Dayang Bunting, and Tuba Island (Azizan et al. 2018; Nizam et al. 2022). According to Figure 1, three central mangrove forests reside within this area on the island: (i) Kisap Forest Reserve; (ii) Kubang Badak; and (iii) Dayang Bunting Island. Only the mangrove channel in Dayang Bunting Island, namely Selat Tuba (with approximately six sq. km), and the mangrove channel in Kisap Forest Reserves, namely Sungai Kilim (approximately 100 sq. km), were selected in this study where Selat Tuba only has small and insignificant human activity, while Sg. Kilim has highly active human activities (Ismail et al. 2018; Suhaimi et al. 2018; Ibrahim et al. 2019). Both Selat Tuba and Sg. Kilim has similar geomorphological properties but has different intensities in anthropogenic activity. Hence, Selat Tuba is the best fit to represent the impact of monsoon seasons solely on mangrove channels, while Sg. Kilim mangrove channel exemplifies the natural impact of monsoon seasons and anthropogenic activity.

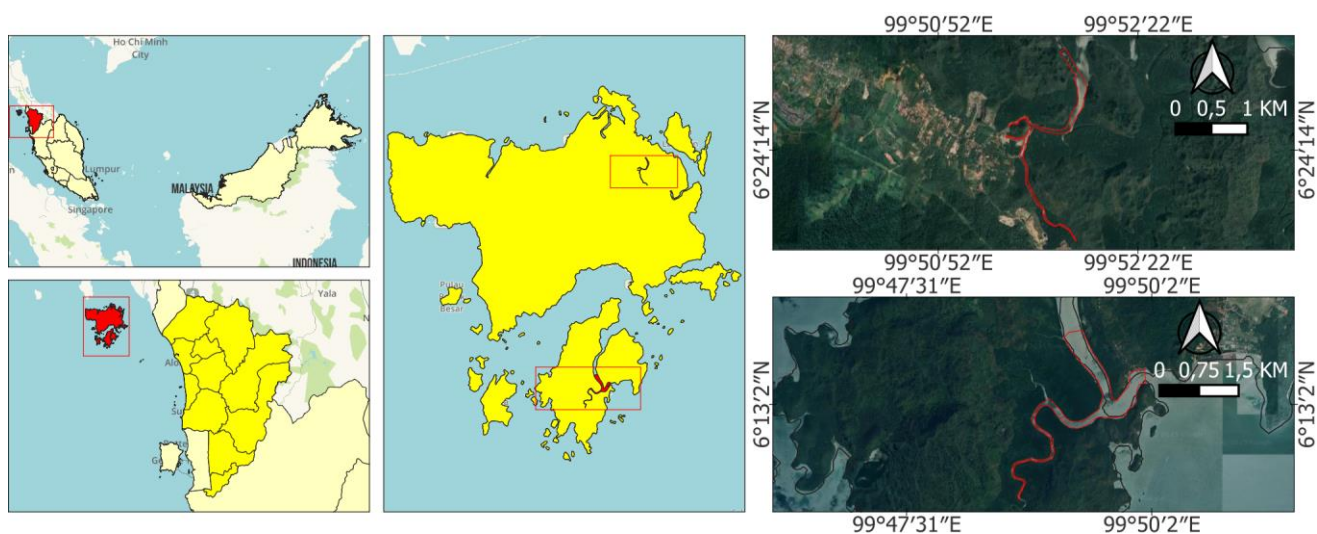


Figure 1. Map showing the location Sg. Kilim (*top right*) and Selat Tuba (*bottom right*), each influenced by distinct anthropogenic activities in Langkawi Island, Kedah Archipelago, Peninsular Malaysia

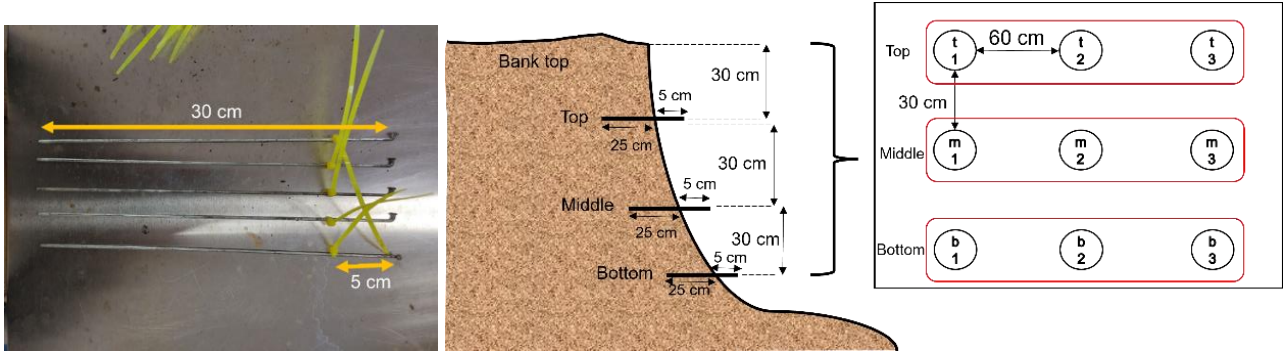


Figure 2. The setting of erosion pins on a 30 cm length metal erosion pins with a 5 cm marker and erosion pins setting on the studied mangrove channel banks. (Adapted from Zhang and Rutherford 2020)

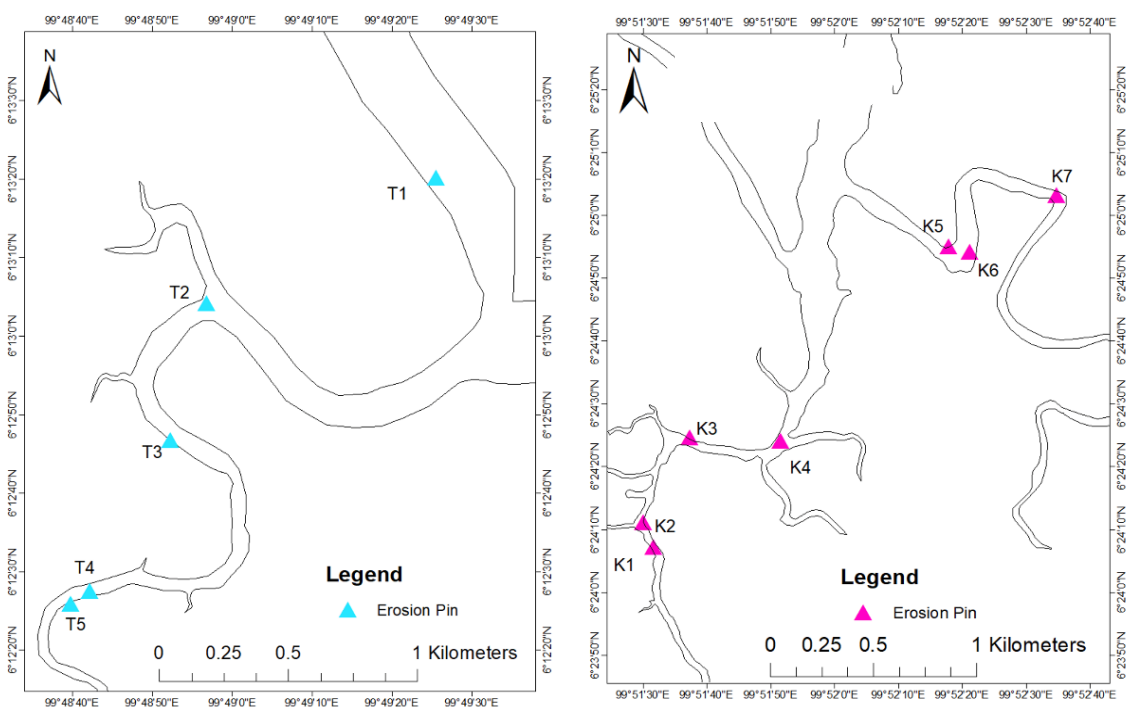


Figure 3. Erosion pin's locations in Selat Tuba and Sg. Kilim sites involved a thorough consideration of channel hydrology, with a specific emphasis on meandering sections where erosion is most prevalent and boat accessibility

Procedures

Erosion pin settings

Field measurements encompass a comprehensive survey of bank erosion to elucidate the erosion rate differences between highly human-active mangrove channels and pristine mangrove channels. Erosion pins are an important, direct, and straightforward method to access initial relative erosion status with minimal cost, not intrusive, and less technical skills are required compared to other complex methods (Myers et al. 2019). This method can help the stakeholders focus on any area that has severe erosion and thus save them time and resources in managing such a vast area (Zhang and Rutherford 2020). Therefore, based on Figure 2, this study utilized stainless steel bicycle spokes with dimensions of 30 cm total length and 2.5 mm diameter (Figure 2) as erosion pins, and these were installed at the mangrove channel bank, with 5 cm left

exposed on the initial implementation. The erosion pins were systematically installed with height division of top, middle, and bottom based on the bank height and equally spaced for 30 cm each, while the replications of each height were equally spaced for 60 cm from one to another (Figure 2).

Field surveys of the pin erosion length reading were conducted every four intervals within a year based on the monsoon seasons in the area where the exposed pin length was measured with a ruler to the smallest unit of 0.01 cm. After a thorough search in the station, if the pin was not present, the reason was determined in the field as either erosion to the entire length of the pin or accumulation on top of the pin. As illustrated in Figure 3, the methodology for selecting pin erosion sites involved a thorough consideration of channel hydrology, with a specific emphasis on meandering sections where erosion is most

prevalent and considering boat accessibility to ensure a comprehensive approach (Vinh and Truong 2014).

Temporal and spatial erosion rates comparison

In order to investigate whether location, sampling points, bank height level, or season significantly influenced erosion processes, a statistical analysis was conducted to compare temporal and spatial differences between Selat Tuba and Sg. Kilim. Prior to selecting an appropriate test (ANOVA or Kruskal–Wallis), the Shapiro–Wilk test was performed to evaluate the normality of the erosion data. This step ensures that the chosen statistical method aligns with the data distribution, thereby providing a robust measure of the significance of any observed differences in erosion rates. The entire process of this study to investigate the lateral erosion mechanism in two distinct mangrove channels is summarised in Figure 4. Since the response data set is large and multifaceted, Estimated Marginal Means (EMM) were used to analyse responses, patterns, and tendencies concerning different pin placements as well as the different seasons. The EMMs offer enhanced insights into mean differences and trends in erosion rates for each combination of factors, thereby aiding in a more nuanced interpretation of the results.

RESULTS AND DISCUSSION

Lateral erosion rates

The findings reveal notable variations in lateral erosion rates among mangrove channel banks, where it is found that the highest annual lateral erosion rates are 0.62 and 0.61 m/year for Selat Tuba and Sg. Kilim, meanwhile, both study areas have minimum annual lateral erosion of as much as 0.03 to 0.06 m/year for Sg. Kilim and Selat Tuba, respectively. In terms of the seasonal lateral erosion, both inter-season and wet season in Selat Tuba recorded 0.30 m/month, representing the highest reading of lateral erosion on the bank in the area, whereas Sg. Kilim only has inter-season as the highest rates of seasonal lateral erosion (0.30 m/month). The summary of the lateral erosion rates for both Selat Tuba and Sg. Kilim are presented in Table 1.

The results of individual sampling points and in-situ representativeness are further illustrated in Tables 2 and 3. Each table highlights the erosion rate of each season (dry, wet and inter-monsoon) according to the height of the bank level (Figure 2) at two different locations. To summarise the annual erosion activity, the table also provides the annual lateral erosion rate generated from the cumulative seasonal erosion rates throughout the year. Therefore, Table 2 shows more details on the lateral bank erosion rate at Selat Tuba, while a detailed breakdown of the lateral bank erosion rate at Sg. Kilim is provided in Table 3.

Initially, an ANOVA approach was considered for analyzing the erosion rates for the study, but the Shapiro–Wilk test indicated that these data were not normally distributed ($p < 0.05$). Consequently, a non-parametric Kruskal–Wallis test was employed to compare erosion levels across categories (location, sampling points, bank height, and season). The Kruskal–Wallis results showed

that sampling point was the only significant factor affecting erosion ($p < 0.001$). A post-hoc Dunn’s test confirmed which specific sampling points differed significantly. In contrast, location, bank height, and season did not exhibit statistically significant effects on erosion ($p = 0.881, 0.339,$ and $0.238,$ respectively). These findings suggest that lateral erosion rates did not vary significantly across different seasons and bank height division in the studied area.

However, the Estimated Marginal Mean (EMM) results revealed interesting nuances, particularly in the comparison between Selat Tuba and Sg. Kilim. Contrary to the general trend observed across the other bank zonation, Selat Tuba exhibited an inverse pattern compared to Sg. Kilim observed higher erosion at the bank middle and bottom zones in the wet season. Meanwhile, Sg. Kilim exhibited higher lateral rates in dry and inter-seasons compared to the wet season, with the bottom zone dominating the lateral erosion. This discrepancy between Selat Tuba and Sg. Kilim is visually evident in the EMM graph, where the inverse patterns are depicted in Figure 5. This underscores the importance of utilising EMMs for a more nuanced interpretation of the data, as overall statistical tests may overlook specific trends. The lack of statistical significance for the main effects in the Kruskal–Wallis test suggests that while Selat Tuba and Sg. Kilim may exhibit different erosion patterns; these differences are not statistically significant when considering the entire dataset.

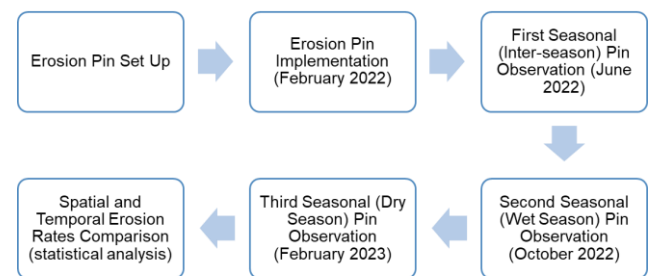


Figure 4. The study design map shows one year’s worth of corrosive work within the mangrove channels to demonstrate the temporal progression and spatial dynamics of the investigated mangrove environment

Table 1. Summary of lateral erosion rates observed with erosion pins for both study areas focusing on stations with the lowest and highest erosion records.

Selat Tuba				
Lateral erosion rates	Inter-season (m/month)	Wet Season (m/month)	Dry Season (m/month)	Annual (m/year)
Max	0.30 (T3)	0.30 (T1)	0.27 (T1)	0.62 (T1)
Min	0.00 (T3)	0.04 (T3)	0.01 (T2)	0.06 (T3)
Sg. Kilim				
Lateral erosion rates	Inter-season (m/month)	Wet Season (m/month)	Dry Season (m/month)	Annual (m/year)
Max	0.30 (K3)	0.21 (K1)	0.25 (K5)	0.61 (K3)
Min	0.00 (K7)	0.01 (K7)	0.01 (K4)	0.03 (K7)

Table 2. Lateral erosion rates of Selat Tuba on top, middle and bottom sections with relation to in-situ bank conditions

Lateral erosion rates with respective bank zones	In-situ bank conditions
<p>T1 Lateral Erosion Rates Comparison with Season and Bank Heights</p> <p>Lateral Erosion Rate</p> <p>Annual (m/year)</p> <p>Dry Season (m/month)</p> <p>Wet Season (m/month)</p> <p>Inter-season (m/month)</p> <p>Top Middle Bottom</p>	
<p>T2 Lateral Erosion Rates Comparison with Season and Bank Heights</p> <p>Lateral Erosion Rate</p> <p>Annual (m/year)</p> <p>Dry Season (m/month)</p> <p>Wet Season (m/month)</p> <p>Inter-season (m/month)</p> <p>Top Middle Bottom</p>	
<p>T3 Lateral Erosion Rates Comparison with Season and Bank Heights</p> <p>Lateral Erosion Rate</p> <p>Annual (m/year)</p> <p>Dry Season (m/month)</p> <p>Wet Season (m/month)</p> <p>Inter-season (m/month)</p> <p>Top Middle Bottom</p>	
<p>T4 Lateral Erosion Rates Comparison with Season and Bank Heights</p> <p>Lateral Erosion Rate</p> <p>Annual (m/year)</p> <p>Dry Season (m/month)</p> <p>Wet Season (m/month)</p> <p>Inter-season (m/month)</p> <p>Top Middle Bottom</p>	
<p>T5 Lateral Erosion Rates Comparison with Season and Bank Heights</p> <p>Lateral Erosion Rate</p> <p>Annual (m/year)</p> <p>Dry Season (m/month)</p> <p>Wet Season (m/month)</p> <p>Inter-season (m/month)</p> <p>Top Middle Bottom</p>	

Table 3. Lateral erosion rates of Sg. Kilim is on top, middle, and bottom sections with relations to in-situ bank conditions

Lateral erosion rates with respective bank zones	In-situ bank condition
<p>K1 Lateral Erosion Rates Comparison with Season and Bank Heights</p>	
<p>K2 Lateral Erosion Rates Comparison with Season and Bank Heights</p>	
<p>K3 Lateral Erosion Rates Comparison with Season and Bank Heights</p>	
<p>K4 Lateral Erosion Rates Comparison with Season and Bank Heights</p>	
<p>K5 Lateral Erosion Rates Comparison with Season and Bank Heights</p>	

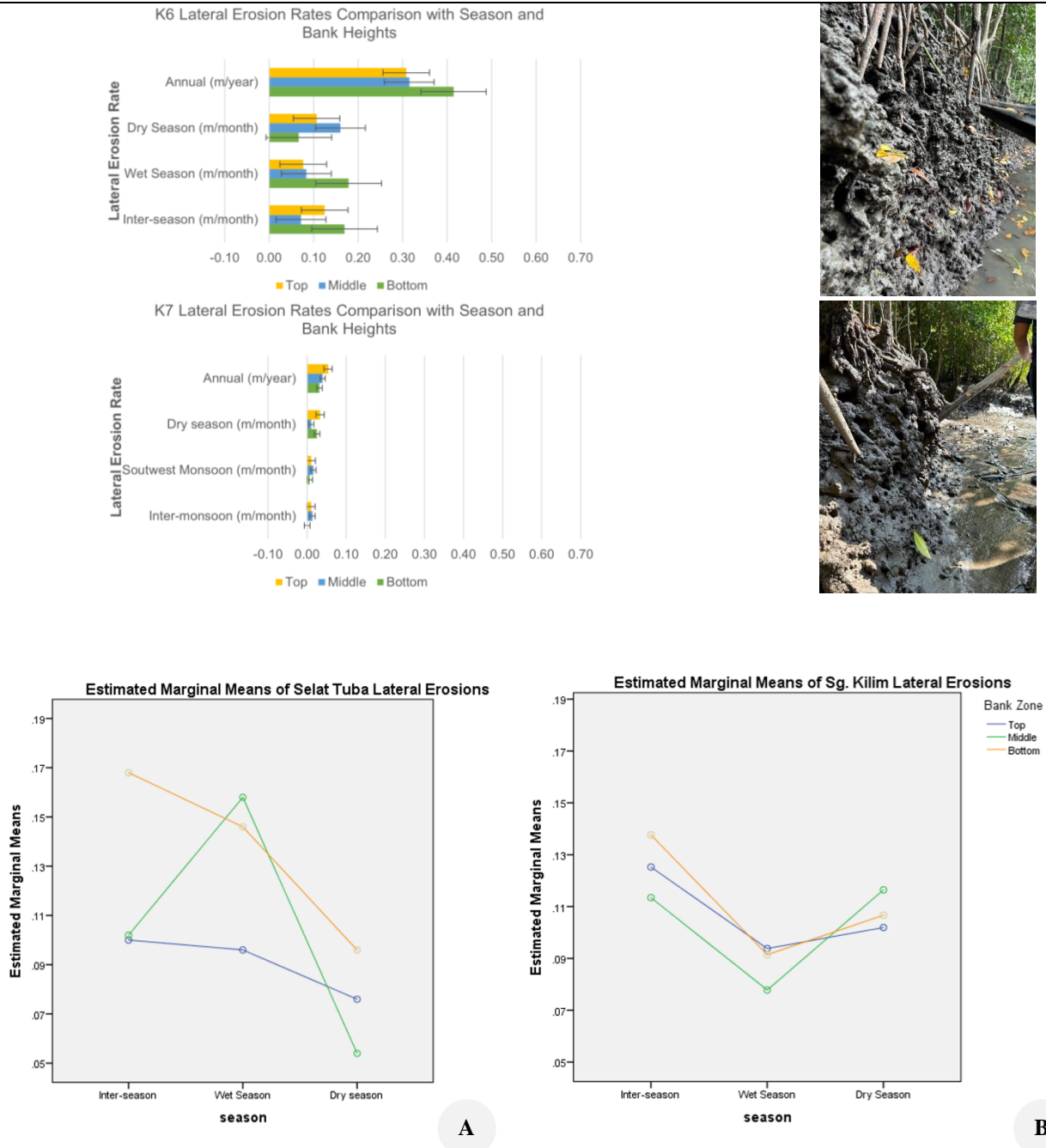


Figure 5. Estimated Marginal Mean (EMM) of A. Selat Tuba; and B. Sg. Kilim lateral erosion across the seasons and bank zonation

The study also observed some of the erosion patterns exhibited by the mangrove channel banks and attempted to categorize them into several types of categories. Mangrove channel bank conditions are distinguished by distinct types that are intricately shaped by a variety of hydrological properties prevalent in the surrounding area. Understanding the complex dynamics that govern these critical coastal ecosystems requires the classification of erosion types.

Figure 6 depicts a visually intuitive representation of the different types of mangrove channel banks based on annual erosion process dominance in various zones of mangrove channel banks. An estimated four types of erosion patterns were identified, and the dominant erosion at different heights of bank level drives the pattern and final shape of the channel banks.

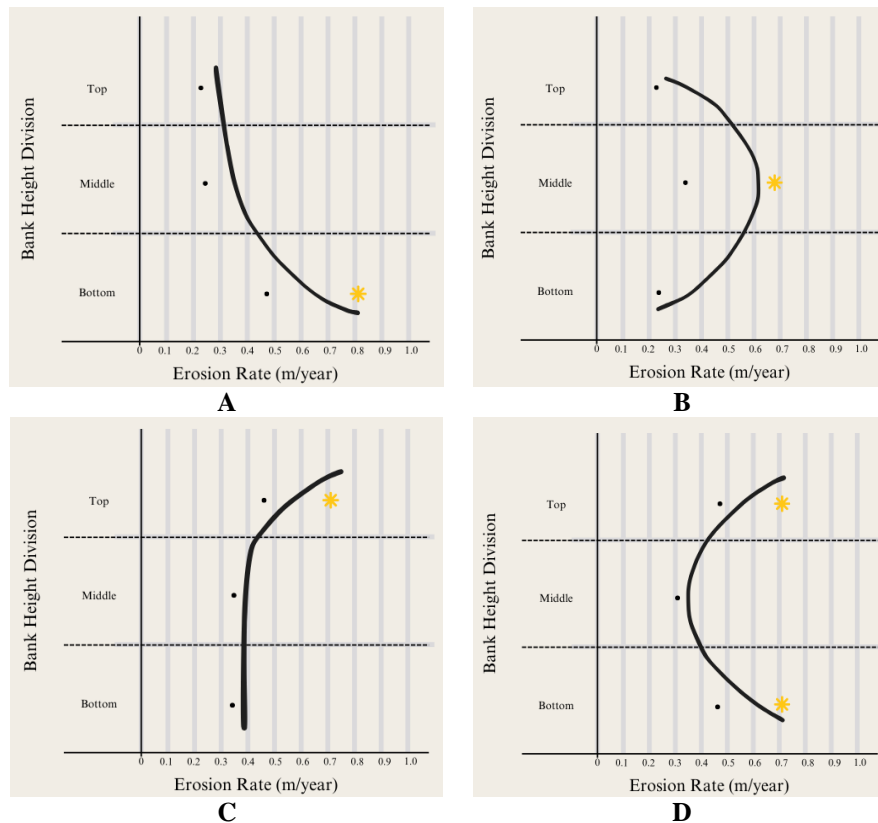


Figure 6. Lateral erosion trends in Selat Tuba and Sg. Kilim is classified into four types where: A. is type (example from T5); B. type ii (example from T4); C. type iii (example from T2); and D. type iv (example from K1), and the asterisk (*) defines the dominant zone of erosion, where type i has bottom erosion zone dominated, type ii is middle erosion zone dominated, type iii has top erosion zone dominated, and type iv have both top and bottom erosion zone dominated

Discussion

T1 in Selat Tuba is seen to be mainly experiencing the fluvial erosion of being located at the intersection of the open water area of Tuba Straits and the mangrove channel; thus, it is experiencing undercutting phenomena for a year cycle, where the bottom erosion is exceeding other erosion in the bank. This has led to a visible effect where bank failure has happened in this area, impacting the mangrove tree on the bank to be uprooted as well (Figure 7). Therefore, the distance from the coastal and open water is seen to be one of the natural factors influencing rates of lateral erosion in mangrove channels, and these rates can be amplified with the SLR, leading to the increasing vulnerability of mangroves at the station (Di Nitto et al. 2014). Meanwhile, another lateral erosion is less than 0.25 m/month across the season for all the bank zones in Selat Tuba station except T3 in inter-season, where the bottom zone experienced 0.30 m/month. This is due to T3 being located on high velocities of water flow in the outer bend of the channel (Engel and Rhoads 2017).

Conversely, in Sg. Kilim, which is famously known as an ecotourism destination, has relatively high lateral erosion, mainly during the dry season (November – March) and inter-seasons (April – June) where these are the peak periods for tourism to experience higher visitors in this area due to less rainfall, sunny and windy weather in Langkawi Island (Sapari et al. 2013). Thus, this area is experiencing a high number of visiting tourists, and indirectly, there is an

increase in boating frequencies, which causes boat wakes to interact with channel banks and lead to erosion (Novak et al. 2021). This can be seen in K3 of Sg. Kilim, which is located near the boat jetty, experiences up to 0.30 m/month of lateral erosion for both top and middle zones in the respective inter-season and dry seasons.

Additionally, despite the wet season, which has relatively higher rainfall, K5 in Sg. Kilim also has higher lateral erosion rates in dry and inter-seasons (0.25 and 0.15 m/month), where this anomaly can be attributed to the location serving as a primary route for tourism activities, with boats frequently engaging in engine revving to attract eagles for feeding, causing the banks to experience the impact of this activity. Notably, K7 is also located along the same channel in Sg. Kilim experiences relatively mediocre lateral bank erosion throughout the one-year cycle (< 0.5 m/year) compared to other stations in the area. This disparity can be linked to the lower frequency of boat activities in the proximity of this station.

The variations of bank conditions are due to the geography of the location of the bank, where outer bends normally have the variation type i (T1, T3, T5, and K6) due to the higher water velocities in this area. Meanwhile, inner bend channels tend to have type iii (T2, K5, K7), signifying lower water velocities and allowing sediment to settle in this area (Hooke 2013; Li et al. 2021). Alternatively, straight channels tend to have type ii (T4), where the lateral erosion in this area is the initialization of channels to

transform into meandering and stabilize. However, K3 and K4 have similar type ii bank conditions despite being located on outer bends, and these sections are reported to have the highest lateral bank erosion in Sg. Kilim (~0.60 m/year). This high erosion rate is proven previously by the high wave energy traveling reported through the boating activities and causing the widening of the channel and bank shifting, indicated by the loss of mangrove territory in the area, which is also a sign the erosion process in the region is exceeding the plant anchoring power (Mohamad et al. 2018; Suhaimi et al. 2018; Kibler et al. 2022). These unusual bank conditions are further explained by the accumulated sediment from bank failure at the bank toe where when the bank collapses, the failure bank material fills up the bank toe by gravity, and this may be carried away by flow or remain deposited on the toe of the bank. According to Figure 8, this theory is demonstrated in Hasegawa (1981), where the bank failure processes can be estimated using a simple assumption that it occurs when the volume of zone A (sediment supply due to bank erosion) becomes equal to that of zone B (deposition).

The mangrove roots mainly dominated in the A area (Figure 8) where traveling water velocities are slowed down during the high tides, causing less erosion process, explaining the less prominent lateral erosion on the top region of the same K3 and K4 station (Arnold and Toran 2018; Kazemi et al. 2021). However, when the tides recede (ebb tide), or advance (flood tide) where the water levels are below the mangrove roots (middle area), the study observed that the erosion amplified with the traveling water and boat wakes impact without protection from mangrove roots and presence of bioturbation activities, explaining how erosion dominated the middle section. Meanwhile, type iv bank conditions are where the bank experiences fluvial erosion (undercutting) on the bottom bank zone but also aerial erosion (top bank zone), and this can significantly come from boat wake impact and sediment properties, where this type only can be seen as illustrated in

Figure 9 at station K1 and K2 that is dominated with coarse gravels on the bank toe.

The variation of lateral channel bank erosion rates in this area is seen to be mainly resulting from three processes: (i) fluvial erosion caused by channel flow's lift and drag; (ii) subaerial erosion caused by dynamic soil moisture conditions, which is defined as weathering and weakening of bank material; or (iii) mass failure of the upper part of the bank due to gravity (Imanshoar et al. 2012). The observed erosion rate differences in the studied area highlight the importance of considering bank zonation in mangrove channel vulnerability assessments, emphasizing the need to consider the bank erosion profile to assess the vulnerability of the mangrove channel bank for tailored conservation and restoration strategies.

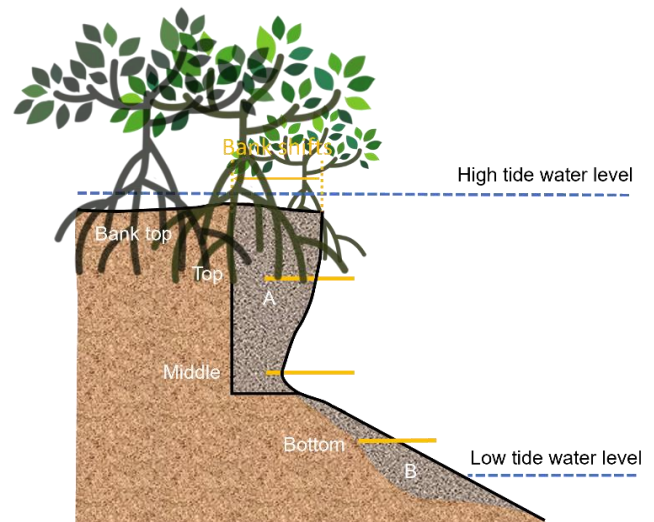


Figure 8. Bank shifting events are based on bank failure theory, where area B accumulates from the failure of area A with vegetation present (Adapted from Hasegawa 1981)



Figure 7. A sediment cluster was found near the bank's bottom with: A. An erosion pin detached with it, indicating the bank failure; and B. Mangrove tree uprooting due to the bank failure at station T1

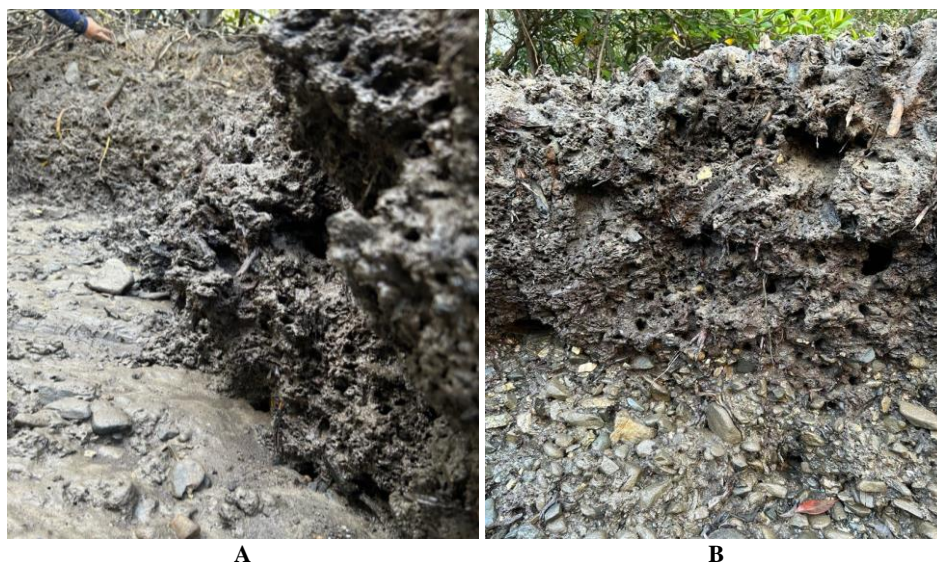


Figure 9. Different bank sediment compositions at: A. K1; and B. K2 cause unique bank conditions, categorized as type iv, that influence the lateral bank erosion patterns

Following that, annual lateral erosion rates in Selat Tuba are seen to be significantly lesser than Sg. Kilim in the dry season has a ratio of 1:2.7, and this can be explained by the increased number of boat frequencies reported by the Langkawi Development Authority (LADA 2023) in Sg. Kilim during this season (November to March). This further signifies that the boating frequencies can suggestively alter and amplify the lateral erosion rates within the area, highlighting the impacts of tourism on mangrove ecosystems. Even though Selat Tuba is close to the open water, it exhibits relatively similar erosion rates despite differing human activities in the respective areas. This implies that in the case of increased human activities in the future, there might be possibilities for worse lateral erosion rates, hence a threat to both the extent and value of mangroves in the area. Hence, the significance of this work is in underlining the need to enhance the management of tourist destinations so that any future tourist development strategies would be sensitive to the problem of lateral erosion in the region.

In conclusion, this research provides further critical and essential information about lateral erosion dynamics of mangrove channels, explicitly focusing on the importance of zonation of channel banks to the sustainability of the mangrove systems. This study also suggests that seasonality contributes to influencing erosion rates, especially in Sg. Kilim, the erosion rates in the area can be amplified with the increase in human activity. The stability of mangrove channel banks becomes not just an ecological concern but a matter of strategic importance for those tasked with managing coastal resources and fostering sustainable practices. Future suggestions include the sediment budget and channel hydrology model development to understand the impact of monsoon seasons, sea level rise, and anthropogenic activity comprehensively on mangrove channels and facilitate the survivability of mangrove ecosystems.

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