Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Impact of Sedimentation on Mangrove Forests in West Coast, Peninsular Malaysia

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ARTICLE INFO

Article history:
Received 27 January 2025
Received in revised form 17 February 2025
Accepted 30 June 2025
Available online 20 July 2025

Keywords:
Sedimentation; mangrove; Avicennia marina; sediment deposition; sediment volume

ABSTRACT

Mangrove ecosystems, known as the rainforests of the sea, are vital coastal habitats providing crucial environmental benefits. However, they face an imminent threat from sedimentation, a complex interplay of natural and human-induced factors. This study explores the multifaceted effects of sedimentation on mangrove health, focusing on Pantai Punggor (1°41'8.75"N, 103° 6'1.22"E) and Pantai Perpat (1°40'26.82"N, 103° 6'42.07"E) in Batu Pahat, Johor, Malaysia. Avicennia marina is a mangrove species affected by sediment deposition, selected for relevance in such zones. UAV photogrammetry was used due to its low cost and great spatial resolution. Data was processed using Global Mapper and Pix4D software, as well as careful mission planning and camera calibration. Sediment characteristics were analysed following ASTM standards, including sieve analysis, specific gravity and moisture content techniques. Mangrove characteristics were assessed by measuring trunk diameter through field data and tree height using UAV-derived Digital Surface and Terrain Models. The results reveal significant disparities between Pantai Punggor and Pantai Perpat, emphasizing the adverse effects of sedimentation on mangrove growth. Pantai Punggor exhibited a higher moisture content of 45% and a lower sediment volume of 1856 m^3 for a 100 m distance, compared to Pantai Perpat with 6.25% moisture content and 2833 m^3 of sediment volume. Furthermore, Pantai Punggor's mangroves displayed taller trees with an average height of 8 meters and wider trunks with an average diameter of 38 cm, in stark contrast to the comparatively stunted growth observed at Pantai Perpat (average height of 5 meters and average trunk diameter of 30 cm). These findings emphasize sedimentation's adverse impact on mangrove health, stressing the need for effective management strategies and conservation efforts. The study advocates for targeted actions to safeguard these critical coastal habitats in Malaysia, including reducing sediment pollution and restoring water flow patterns. Recognizing mangroves' role in coastal resilience and ecological balance, ongoing research and dedicated conservation measures are essential to protecting these unique and fragile ecosystems.

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https://doi.org/10.37934/ard.138.1.151161

1. Introduction

The mangrove ecosystems in Malaysia, renowned as the forests of the sea, hold profound ecological significance and are prominently distributed along the country's coastal regions. These unique coastal forests play a pivotal role in Malaysia's rich biodiversity, offering habitat to a diverse array of flora and fauna, including a myriad of fish species, birds and crustaceans. Furthermore, they serve as essential nurseries for commercially valuable fish species, supporting the local fishing industry. However, these invaluable ecosystems are under threat from various sources, with sedimentation emerging as a significant concern. The sedimentation issue results from a combination of natural processes, such as tidal action and river discharge and anthropogenic activities, including deforestation and land-use changes, which collectively disrupt the balance of sediment deposition and place these ecosystems at risk.

The health of mangroves can be impacted by sediment transport in many ways. Excessive sediment deposition can change the soil's physical and chemical composition, which decreases the nutrients and oxygen available to mangrove roots [1]. As a result, mangroves may grow more slowly, become more susceptible to pests and illnesses and eventually die [2].

Along with soil characteristics, sediment transport can affect the hydrology of mangrove habitats. Basyuni *et al.,* [3], sediment deposition can obstruct waterways and reduce flow, which can lead to increased salinity and waterlogging in certain areas and decreased salinity and desiccation in other areas. This could alter the distribution of mangrove species and have a detrimental effect on the environment's biodiversity. To combat the detrimental impacts of sediment transportation on the health of mangroves, many management strategies have been devised. To reduce silt migration downstream, sediment-capturing infrastructure such as sediment ponds and check dams is deployed [4]. Replanting damaged mangrove areas and sustainable land use practices are two more strategies for lowering sedimentation rates [3].

Finally, the health and viability of Malaysia's mangrove ecosystems are seriously threatened by sediment transportation. Reduced mangrove growth and biodiversity may be the result of sediment deposition's effects on soil properties and hydrology, which highlights the need for effective management strategies to offset these negative effects. Since there have been only a few studies conducted on mangrove growth in the study area, it has become necessary to undertake this research. Previous research has indicated that sediment transport may contribute to the degradation of mangrove areas so this study endeavours to evaluate the effects of sedimentation on mangrove growth and shed light on the adverse impacts observed.

1.1 Mangrove Ecosystem Characteristic

Mangrove ecosystems are rich and unique coastal habitats characterized by their remarkable ability to adapt to harsh environmental conditions. These ecosystems typically consist of six different varieties of mangroves and ten plant species related to the habitat, totalling 16 species in total. The composition of these species can vary between different locations, with some areas exhibiting higher diversity. Notable among the prevalent species are *Avicennia marina*, *Suaeda maritima* and *Sesuvium portulacastrum*. These mangroves are critical components of coastal ecosystems and provide essential ecological services. The findings from earlier studies provide important perspectives on the species composition and distribution in the mangrove habitat [5]. Figure 1 shows the schematic overview of the bio-morphodynamic modelling.

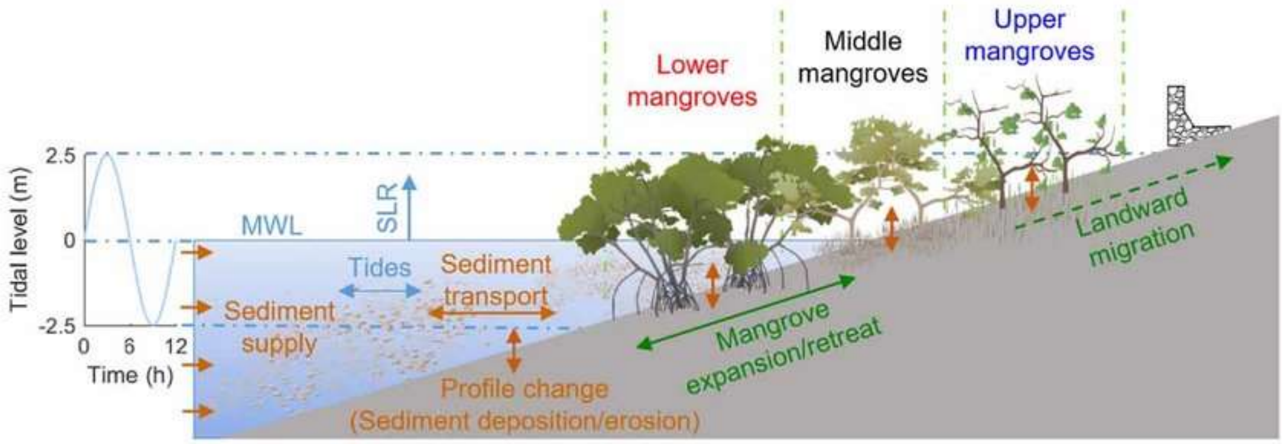

Fig. 1. Schematic overview of the bio-morphodynamic modelling [6]

One of the defining characteristics of mangrove habitats is their ability to thrive in challenging conditions. Mangroves have evolved to cope with high temperatures, salinity, low oxygen levels and contaminated environments [7]. Their roots are specially adapted to handle waterlogged soils, which can vary widely in salinity, ranging from 2% to 90% [5]. These adaptive features make mangroves resilient to sea-level changes and extreme weather events. Their unique physiology allows them to filter and trap sediments and nutrients, making them crucial for water quality and shoreline stabilization.

Mangrove root structures significantly influence hydrodynamic conditions and sediment deposition by reducing wave energy and enhancing sediment retention. Their intricate networks slow water flow, allowing suspended particles to settle and stabilize coastal environments. Mangrove root structures significantly influence hydrodynamic conditions and sediment deposition by reducing wave energy and enhancing sediment retention. Their intricate networks slow water flow, allowing suspended particles to settle and stabilize coastal environments. Tan *et al.,* [8] investigated artificial mangrove root models using Computational Fluid Dynamics (CFD) and experiments, revealing that higher root porosity reduces flow resistance and improves debris trapping. These findings highlight the role of mangrove roots in sediment transport, coastal protection and maintaining shoreline stability and water quality.

The physical appearance of mangrove forests can vary, with mangrove trees ranging in size from small shrubs to towering giants that can reach heights of 5 to 25 meters. The specific height and structure of the mangroves depend on various factors, including the age of the forest and local environmental conditions. These diverse characteristics provide a wide range of niches for various wildlife species, making mangrove ecosystems a hub for biodiversity. Additionally, mangrove habitats are known for their role in supporting a wide array of aquatic and terrestrial species, making them vital for the overall health and resilience of coastal ecosystems worldwide [9].

1.2 Sediment Transport

Sediment transport is a dynamic and complex process that is primarily driven by the forces of fluid flow, whether from water, wind or human activities. In the context of water-driven sediment transport, rivers and streams are the primary conduits for the movement of sediments [10]. River flow exerts shear stress on the riverbed, causing sediment particles to become dislodged and subsequently transported downstream [11]. This process, known as fluvial transport, is essential for shaping river channels and distributing sediments along river networks. It plays a vital role in the redistribution of soil and sediments across landscapes. A component of the sandy marine beach is shown in Figure 2.

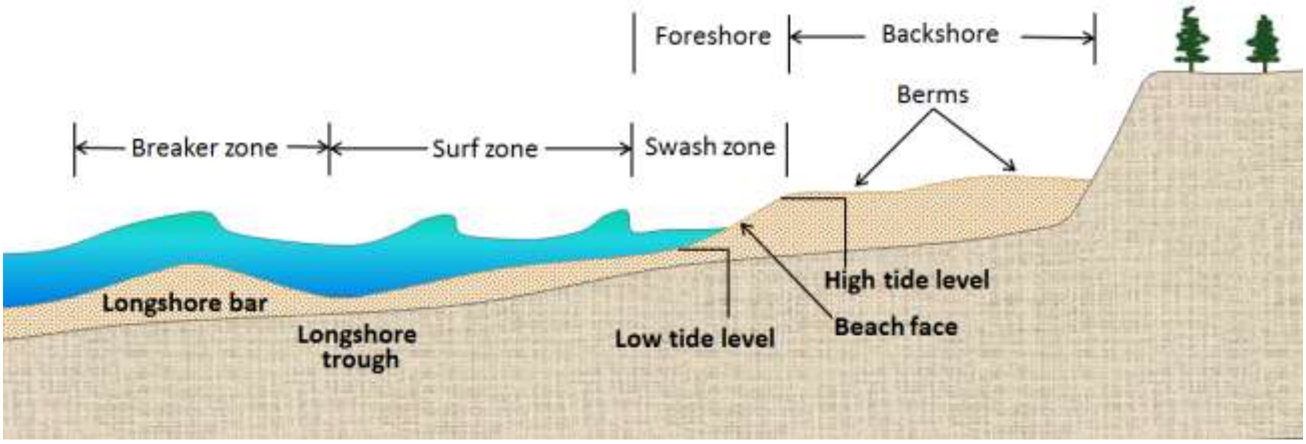

Fig. 2. The components of a sandy marine beach [12]

Coastal sediment movement is characterized by the zigzag pattern of particles along beaches due to wave action and their orbital motion [13]. Longshore sediment transport contributes to the formation and evolution of barrier islands and beaches, impacting the dynamics of coastal ecosystems. Additionally, tidal currents in estuaries and tidal flats carry sediments, redistributing them within these coastal systems [14]. Coastal sediment transport is crucial for maintaining the balance and structure of shoreline environments.

Various numerical models, such as sediment pulse models and Dam Removal Express Assessment Models (DREAM), have been used to simulate sediment movement, considering factors like grain size distribution. Empirical and numerical approaches, including pressure fluctuation-erodibility indices, improve scouring predictions, enhancing structural reliability in dam environments [15]. These methodologies also provide insights into coastal sedimentation, which impacts mangrove ecosystems.

In arid and coastal regions, sediment transport driven by wind is a common phenomenon. Loose particles, such as sand and dust, are easily entrained and carried by wind gusts [16]. Aeolian processes, including saltation (hopping and bouncing of particles) and suspension (particles suspended in the air), can transport sediments across significant distances [17]. This wind-driven sediment transport can have a range of consequences, from shaping desert landscapes to impacting air quality and human health, particularly in areas prone to dust storms [18]. Understanding these different modes of sediment transport is essential for managing and mitigating their effects on both natural and human-altered environments.

1.3 Sediment Depositions Affecting Mangrove

Mangroves play a crucial role in influencing sediment deposition and, in turn, are significantly impacted by sediment rates. These ecosystems are nature's own way of regulating sediment transport and maintaining the elevation of coastal areas. They effectively reduce sediment movement by slowing down water flow and providing a habitat where suspended sediments can settle. The intricate root networks and prop roots of mangroves act as natural barriers, trapping sediments and promoting sediment deposition within their vicinity [19]. This process not only helps mangrove ecosystems grow taller but also leads to the formation of mudflats and marshy regions in coastal areas.

Sediment accumulation rates in mangrove environments are influenced by a range of factors, including tidal patterns, vegetation density and hydrodynamics [20]. These variables interact to determine the extent and rate of sediment buildup within the mangrove ecosystem. Such sediment deposition is pivotal for the overall health and development of mangroves, allowing them to thrive in their unique coastal habitats and providing essential ecological services.

Furthermore, mangrove ecosystems are known for their capacity to enrich sediment with organic matter and nutrients. These nutrients are absorbed and retained by mangroves, resulting in a nutrient-rich environment that supports diverse organisms [21]. The complex nutrient cycling processes in mangrove sediments play a vital role in maintaining the health of the ecosystem, benefiting both the flora and fauna that call these habitats home. In addition to their ecological significance, mangroves serve as natural barriers against coastal erosion by reducing wave energy and preventing shoreline erosion through sediment accumulation, making them indispensable in safeguarding coastal communities and infrastructure [22]. The intricate relationship between mangrove ecosystems and sediment rates underscores their importance in coastal management, conservation efforts and the broader environmental context.

1.4 Existing Research at Pantai Punggor and Pantai Perpat

The study by Din *et al.,* [23] highlights the significant impact of sediment deposition on the ecological health of mangroves in the study area. The dynamic processes of accretion and erosion play pivotal roles in shaping their condition.

The research conducted by Kaamin *et al.,* [24] builds on this insight and describes empirical observations from studies conducted in the same area. The research documents tangible changes in the shoreline morphology over time, which supports the idea that the interaction between sediment dynamics and coastal features is a dynamic and evolving process.

In addition, the use of UAV photogrammetry is proving to be a game-changing tool, offering a fresh approach to accurately measure sediment volumes and track shoreline fluctuations with unparalleled precision and efficiency [25]. This technology's potential goes beyond that, as it also enables the assessment of vertical vegetation structure, such as the determination of tree heights, by creating and analysing Digital Terrain Models (DTM) and Digital Surface Models (DSM). This multi-dimensional functionality highlights the versatility and practicality of UAV-based techniques in enhancing our knowledge about coastal ecosystems and their complex dynamics.

2. Materials and Methods
2.1 Description of the Site Location

Pantai Punggor and Pantai Perpat were selected as the study regions at the outset of the investigation. One of Batu Pahat's places with significant erosion and accretion phenomena is Pantai Punggor and Pantai Perpat [25]. The coastline in the Batu Pahat region varies significantly [26]. The shoreline changes study by Mokhtar *et al.,* [27] shows how the shoreline at both beaches can vary in just one year, affecting the mangrove condition there [26]. Both sites were identified as undisturbed and disturbed areas. Pantai Punggor represents the undisturbed area because it is not disturbed by sediment deposition, while the disturbed area (Pantai Perpat) is disturbed by sediment deposition. The species of mangrove that have been examined for this study was Avicennia marina, due to its behaviour in the seaward zone near the sediment deposition area [28]. Figure 3 shows the details of the selected locations for this study.

(a)

(b) (c)

Fig. 3. Figure (a) shows the location of Pantai Punggor (left) and Pantai Perpat (right) (b) Condition of Pantai Punggor (undisturbed area) (c) Pantai Perpat (disturbed area)

2.2 UAV Photogrammetry

This method was selected mostly because of the advancements in UAV photogrammetry, including its cost-effectiveness, versatility and high spatial resolution, particularly for small and medium areas [27]. Careful mission planning, taking into account camera calibration and flight path optimization, was essential for obtaining the best possible data. This study also took advantage of the importance of GCPs in improving the accuracy of photogrammetric outputs [29]. Using Pix4D and Global Mapper, two photogrammetric programs, the data from the aerial photographs was processed. Special attention was paid to including GCP coordinates in the data processing procedure to increase accuracy.

2.3 Characteristics of Site Location
2.3.1 Sediment characteristics

The sediment sample for this investigation was taken from the shorelines of Pantai Punggor and Pantai Perpat using a hand auger. Following ASTM International's Standard Practice for Field Collection of Soil Samples for Subsequent Lead Determination (ASTM E 1727) [30], soil samples were collected. Sieve analysis, specific gravity and moisture content techniques were employed to determine the soil samples' particle size distribution. The Standard Test Method for Particle-Size Analysis of Soils (ASTM D 422) [31] was followed in conducting the tests. Extra characterization of the sediment was also determined by using the sediment's volume determination from the Global Mapper analysis.

2.3.2 Mangrove characteristics

For the mangrove sample, the data collection was done along 100 m of the coastline area for both locations. Mangrove trunks were examined based on their diameter and height. The trunk diameter was determined by field data collection by calculating the average diameter of mangroves' trees at Pantai Punggor and Pantai Perpat. While the height of the tree was determined by utilizing the UAV photogrammetry method in order to create the DSM and the DTM [32]. By applying the method described by Ruzgienė *et al.,* [32], the height of the tree can be determined by subtracting the height of the DTM from the DSM. The accuracy of the model was determined by the root mean squared error (RMSE) of the maps.

3. Results

3.1 Sediment Characteristics

Based on the results of laboratory testing, it was discovered that, on average, from the sieve analysis, the particle size distribution for the Pantai Punggor sample included 76% silt and clay and only roughly 24% fine sand. The soil particle's average grain size was 0.08 mm. While for the Pantai Perpat area, the soil particles' contained sand and gravel for 70%, with 57% of it being gravel and the grain size was 1.59 mm. Mangroves prefer to establish themselves in fine clay and alluvial soil, while they can also grow in sandy soils [33]. Table 1 represents the summary results for sieve and specific gravity tests.

Table 1
Sieve analysis and specific gravity result

Site Location	Sieve Analysis (mm)	Specific Gravity (Gs)	Type of Soil
Pantai Punggor	0.15 – 0.0063	2.73	Inorganic clay
Pantai Perpat	2.0 - 1.18	2.66	Sand and gravel

Figure 4 illustrates the moisture content obtained, with 45% of the moisture contained in the sediment sample from Pantai Punggor and just 6.25% of the moisture content in Pantai Perpat. The results for the volume of sediment at Pantai Punggor were 1856 m^3 for 100 m of distance, while Pantai Perpat, on the other hand, measured 2833 m^3. From the results of the sediment volumes, it can be concluded that the deposition of sediment has an effect on the moisture content and will adversely affect mangrove growth.

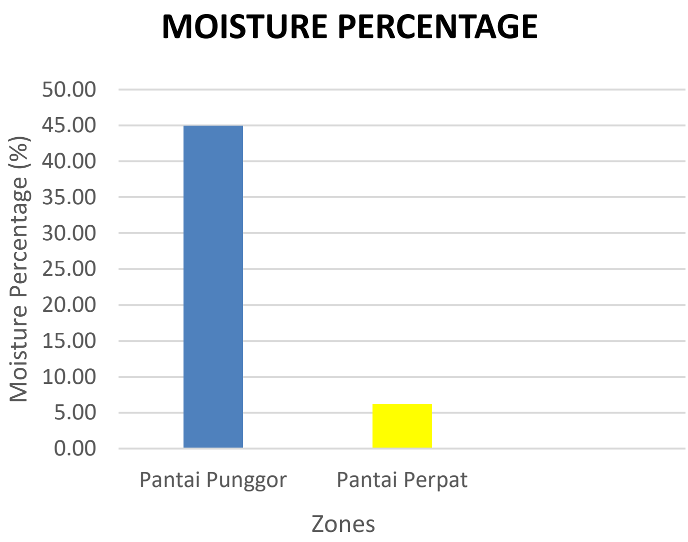

Fig. 4. Percentage of moisture content for Pantai Punggor and Pantai Perpat

3.2 Mangrove Characteristic

The data derived from Figure 5 indicates a marked discrepancy in the average height of mangrove trees between Pantai Punggor and Pantai Perpat. Specifically, the average height recorded at Pantai Punggor stands at 8 meters, notably surpassing the comparatively lower average height of 5 meters observed at Pantai Perpat.

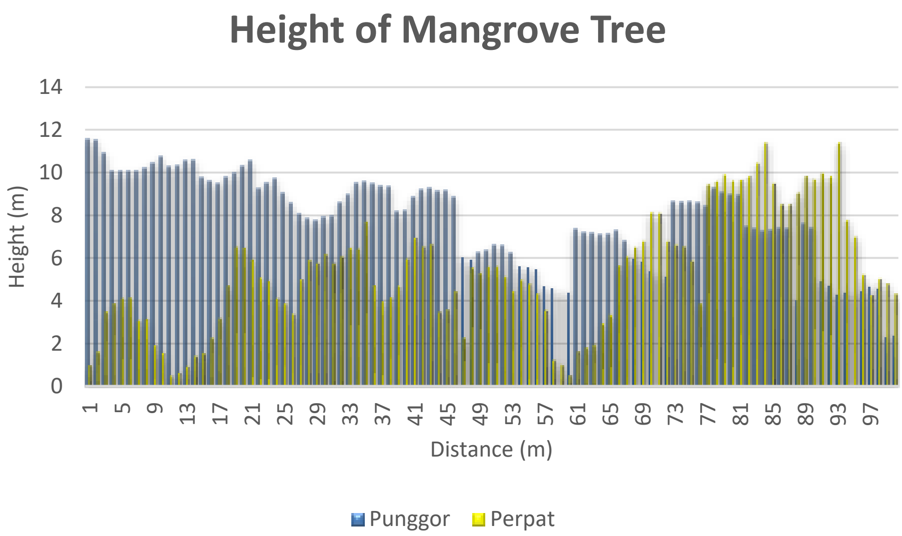

Fig. 5. Tree profile for Pantai Punggor and Pantai Perpat

Figure 6 presents a clear depiction of the notable disparity in trunk diameter observed between Pantai Punggor and Pantai Perpat. The data highlights a discernible contrast, with the former exhibiting an average trunk diameter of 38 cm and the latter displaying an average of 30 cm, emphasizing substantial variation between the two locations.

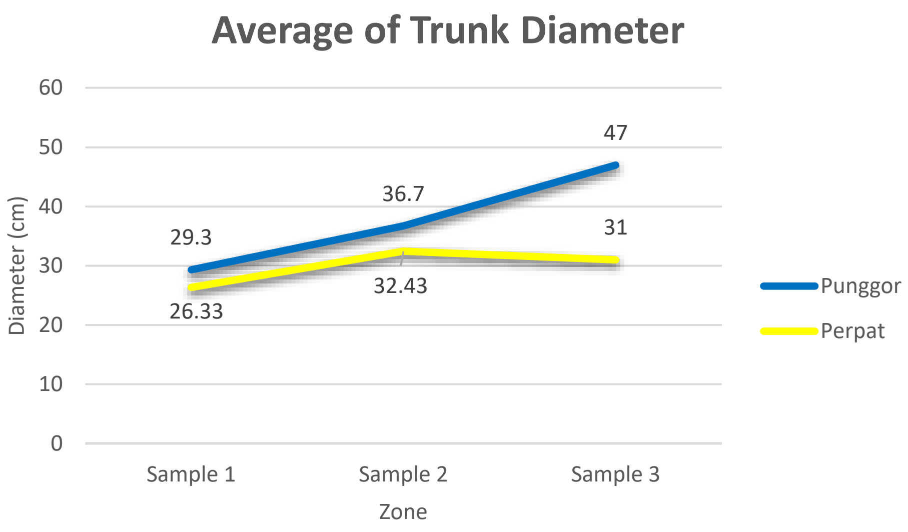

Fig. 6. Average trunk diameter for both site locations

4. Conclusions

Therefore, this study was to evaluate the effects of the sedimentation on mangrove growth. The study found that mangrove growth has been adversely affected by sediment deposition. As we can see in the result, the growth rate of both beaches was differentiated by the presence of excessive sediment deposition. Pantai Perpat with more volume of sediment deposition shows slower or stunted growth of the mangrove tree compared to Pantai Punggor. In conclusion, this study underscores the urgent need for conservation measures to protect the vital mangrove ecosystems in Malaysia. The study specifically delves into the complex impacts of sediment transport on mangrove forests, revealing that excessive sediment deposition might alter soil properties, limiting nutrient and oxygen availability for mangrove roots and risking stunted growth and increased susceptibility to pests and diseases. These findings emphasize on the role of local authorities such as Jabatan Perhutanan and Jabatan Pengairan dan Saliran on the necessity of effective management strategies, urging conservation efforts to prioritize reducing sediment pollution and restoring water flow patterns within mangrove ecosystems. Recognizing the crucial role of mangroves in coastal resilience and ecological balance, the study advocates for ongoing research by other studies from other universities and dedicated conservation measures to safeguard these unique and fragile coastal habitats in Malaysia and beyond.

Limitations arise due to the dense nature of mangrove habitats, which poses challenges in obtaining field data as the thick vegetation obstructs access. Additionally, while UAV monitoring offers a promising avenue for data collection, concerns persist regarding the accuracy of the gathered data. Moreover, the sampling process is constrained by the necessity to conduct collections during periods of lowest tide, adding logistical complexity to the research endeavour. For a recommendation for the future study, a systematic and proper schedule to collect data need to be prepared in order the sample can be collect in a safe and good condition. Plus, with a proper schedule, any circumstances such as blur or cache images can be avoided. This is because the images are important in order to create a good orthomosaic that can lead to a good and accurate data for DSM and DTM.

Acknowledgement
This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) and Tier 1 Grant (Vot Q396) and GPPS (Vot Q303).

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