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UNIVERSITI TEKNOLOGI PETRONAS

DETERMINATION OF MANGROVE ADEQUACY IN DISSIPATING WAVES ALONG KEDAH COASTLINE

by

ERNIE AMIRA BINTI KAMIL

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DETERMINATION OF MANGROVE ADEQUACY IN DISSIPATING WAVES ALONG KEDAH COASTLINE

by

ERNIE AMIRA BINTI KAMIL

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AUGUST 2022

DECLARATION OF THESIS

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I ERNIE AMIRA BINTI KAMIL

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Name of Supervisor
Dr Husna binti Takaijudin

Date : 12th October 2021

Date : 15th October 2021

DEDICATION

In memory of my late Yak,

who inspired to live this adventure out,
who sourced the mental strength throughout,
who left just when this journey was newly ventured and started,
this is for you.

Al-fatihah.
(19012019)

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ABSTRACT

Mangroves are widely acknowledged for their ability in attenuating wave. The protection function that mangroves provide is evident where the mangrove-shielded areas encountered minimal damages compared to the unprotected coastlines. However, studies on the adequacy of mangroves in providing optimum coastal buffer especially along the Kedah coastline remain scarce. This study hereby aims (1) to analyze the distribution and characteristics of mangrove along the Kedah coastline, (2) to determine the wave height reduction across the mangrove forests along the Kedah coastline, and eventually (3) to determine the adequacy of mangrove band width for optimal protection along the Kedah coastline using Bao's formula. Kedah, which was previously affected during the 2004 Indian Ocean Tsunami has been undertaken as the study site. Mangrove characteristics were assessed during field assessment and Landsat-8 OLI images were utilized for mangrove mapping. Later, incident and transmitted wave heights were analyzed to study the reduction by mangroves. Bao's formula was further incorporated to assist in determining mangrove adequacy upon respective wave conditions and mangrove structures. A total area of 5,568.12 ha of mangroves was discovered with dense coverage growing along Merbok River, Kuala Muda and Ayer Hangat, Langkawi. Clearance of mangrove in Kuala Kedah, mangrove defoliation in Jerlun, scarp formation in Merbok, bamboo as replantation technique in Kuala Teriang and sand topping the muddy area in Sungai Melaka have been spotted. The highest shoaling and refracted wave heights of 1.05 m and 0.92 m respectively were analyzed in both Jerlun and Sungai Daun. While less transmission occurred in Kangkong with wave height of 0.68 m, Jerlun, however, recorded the greatest transmission with 0 m wave height. Jerlun, which possesses high density, canopy closure, and maximum band width showed the best performance with a 100% reduction rate. Meanwhile, the lowest dissipation performance of 33.5% was marked by Kangkong. A comparison between the required and current band width of mangroves

was made. The findings revealed that most of the locations had insufficient protection over the minimum band width. Therefore, replantation is needed where the coverage is low to ensure optimum protection towards the coastline.

ABSTRAK

Bakau diakui secara meluas atas keupayaannya dalam memecahkan ombak. Fungsi perlindungan bakau terbukti apabila kawasan yang dibentengi bakau mengalami kerosakan minima berbanding persisir pantai yang tidak dilindungi. Walau bagaimanapun, kajian mengenai kecukupan bakau dalam menyediakan penampan pantai yang optima terutamanya di sepanjang pantai Kedah adalah terhad. Oleh itu, kajian ini bertujuan (1) untuk menganalisa taburan dan ciri-ciri bakau di sepanjang pantai Kedah, (2) untuk menentukan kadar pengurangan ketinggian ombak di sepanjang pantai Kedah dan akhirnya (3) untuk menentukan kecukupan bakau dalam memberi perlindungan yang optima di sepanjang pantai Kedah dengan menggunakan formula Bao. Kedah yang pernah terkesan semasa Tsunami Lautan Hindi pada tahun 2004 telah dipilih sebagai tempat kajian. Ciri-ciri bakau telah dinilai semasa penilaian lapangan dan imej Landsat-8 OLI telah digunakan dalam penghasilan peta taburan bakau. Seterusnya, ketinggian ombak sebelum dan selepas menelusuri bakau telah dianalisa untuk mengkaji pengurangan ombak oleh bakau. Formula Bao selanjutnya digunakan untuk menentukan kecukupan bakau berdasarkan keadaan ombak dan struktur bakau. Keluasan kira-kira 5,568.12 hektar bakau telah diterokai dengan liputan yang besar tertumpu di sepanjang Sungai Merbok, Kuala Muda dan Ayer Hangat, Langkawi. Penebangan bakau di Kuala Kedah, daun bakau meluruh di Jerlun, pembentukan hakisan di Merbok, buluh sebagai teknik penanaman semula di Kuala Teriang serta pasir yang menutupi permukaan lumpur di Sungai Melaka telah dikesan sepanjang penyelidikan di tempat kajian. Pembentingan dan pembiasan ombak yang tertinggi, masing-masing dengan ketinggian 1.05 m dan 0.92 m direkodkan di Jerlun dan Sungai Daun. Ombak yang merentasi hutan bakau di Kangkong mencatat ketinggian sebanyak 0.68 m, sementara ombak dengan ketinggian 0 m direkodkan selepas melepasi hutan bakau di Jerlun. Jerlun yang memiliki kepadatan, penutupan kanopi dan kelebaran hutan bakau yang tinggi menunjukkan prestasi terbaik dengan kadar pemecahan ombak

sebanyak 100%. Sementara itu, kadar terendah sebanyak 33.5% direkodkan oleh Kangkong. Perbandingan antara kelebaran bakau yang diperlukan dan kelebaran semasa bakau menunjukkan bahawa kebanyakan lokasi tidak mempunyai perlindungan yang mencukupi dari segi kelebaran minimanya. Penanaman semula diperlukan di kawasan bakau bertaburan rendah bagi menjamin perlindungan yang optima.

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LIST OF ABBREVIATIONS

DBH	Diameter at Breast Height
DID	Department of Irrigation and Drainage
DVI	Different Vegetation Index
FDI	Forest Discrimination Index
GARI	Green Atmospherically Resistant Index
GDP	Gross Domestic Product
GF-2	GaoFen-2
GIS	Geographic Information System
GPS	Global Positioning System
IOT	Indian Ocean Tsunami
IPVI	Infrared Percentage Vegetation Index
Landsat 8 OLI	Landsat 8 Operational Land Imager
Landsat ETM+	Landsat Enhanced Thematic Mapper Plus
Landsat MSS	Landsat Multispectral Scanner
Landsat TM	Landsat Thematic Mapper
LISS IV	Linear Imaging and Self-Scanning Sensor IV
MLC	Maximum Likelihood Classification
MMFR	Matang Mangrove Forest Reserve
MODIS	Moderate Resolution Imaging Spectroradiometer
NDII	Normalized Difference Infrared Index
NDVI	Normalized Different Vegetation Index
NHC	National Hydrographic Centre, Malaysia
NSWE	Non-Linear Shallow Water Equation
OVBM	Optimized Variational Boussinesq Model
RGB	Red, Green, and Blue
RVI	Ratio Vegetation Index
SPM	Shore Protection Manual
SPOT 5	Satellite Pour I'Observation de la Terre
SWAN	Simulating Waves Nearshore

USGS	U.S. Geological Survey
WFI	Wetland Forest Index

CHAPTER 1

INTRODUCTION

1.1 Overview

Chapter 1 describes an overview of the study, which covers the background of the study, the problem statement that initiates the whole study, research objectives, scope of the study, and significance of the study.

1.2 Background of Study

Mangrove forests are unique ecosystem linking the land and the sea. Mangroves in Peninsular Malaysia are mainly occurring along the west coast, dominantly in the coasts of Perak, Selangor, Johor, and Kedah. The east coast of Peninsular Malaysia is exposed to energetic wave actions of the South China Sea, while the west coast has a calmer wave since it is bordered by the Straits of Malacca with limited wind fetch [1]. These wave patterns might result in the widespread coverage of mangroves on the west coast [2]. In Sarawak, most mangroves are found at the estuaries of Rajang and Trusan - Lawas rivers. Meanwhile, Sabah has the largest distribution of mangroves in Malaysia [3] that grow abundantly in the northeast.

Mangroves are commonly found fringing the estuaries and coastlines up to 5 km landward [4] and grow along sheltered coasts in saline soil and brackish water [5, 6]. This vegetation is tolerant to saline environments that enable them to grow in the tidal zone. The root system provides expansion that contributes to the physical balance of mangroves in the soft and unstable mud, withstanding strong winds, currents, and storms. Mangroves offer important ecosystem services and functions that benefit the surrounding communities. They serve as a natural protection barrier against the erosive wave, strong coastal wind, tsunamis, torrential storms, and other natural disasters such as, Typhoon Haiyan, Indian Ocean Tsunami, Cyclone Bulbul etc.

The 2004 Indian Ocean Tsunami (IOT) is commonly associated to emphasize the role of mangroves in acting as the first line of coastal protection. Malaysia escaped the massive destruction as experienced by other affected countries such as Indonesia, Sri Lanka, and India during the catastrophic events, even though the damage was still significant. Despite its proximity to the epicentre of the tsunami, Malaysia suffered less destruction since it was shielded by the wide land mass of Sumatera. The damages were also minimized by the natural protection from the dense and healthy mangroves along the coastline, which slowed down the tsunami strikes and safeguarded the coastline [7].

Indeed, the devastating 2004 IOT has not only left a significant mark on the coastal management of Malaysia but also instilled an awareness of disaster-related issues and geared up the early planning for preparedness and mitigation actions in confronting any future calamities that are beyond our control. Besides, this has also become a remarkable point for the government in recognizing and valuing the mangrove ecosystem as the first line of coastal defence, which is not only limited to tsunami cases but also including other calamities.

1.3 Problem Statement

Mangroves are acknowledged for their ability in attenuating waves. Their complex root configuration serves as a drag force to eventually reduce the rate of incoming waves. As such, the dense presence of healthy mangroves at the frontier can reduce the amplitude of waves that struck the coastline. This is especially evidenced after the traumatic IOT that claimed thousands of lives and left great damages, where the mangrove-shielded areas encountered minimal damages compared to the unprotected coastlines. Therefore, in response to the tragedy aftermath, hectares of mangroves have been replanted in the coastline of Malaysia.

Nonetheless, studies on the adequacy of this vegetation as coastal protection remain scarce. To date, only three studies have highlighted the adequacy of mangroves in providing protection to the nearest coastal area. Bao assessed mangrove sufficiency in Vietnam [8], while Shahruzzaman [9] and Shabuddin [10] assessed mangrove sufficiency in Perak and Kedah, Malaysia, respectively. Nonetheless, only Rhizophora's performance was evaluated in Perak with negligence of mangrove density in the analysis of dissipation. A study on adequacy in Kedah, on the other hand, was lacking the real wave data and the analysis was mainly based on the assumption value of wave height. This shows that no complete studies have addressed the adequacy of mangroves, specifically along the Kedah coastline.

Thus, the status of mangroves is of great concern due to numerous anthropogenic factors and natural disaster threats. In fact, mangroves are being cut down to make room for future development, considering the fact that this vegetation has little to zero economic benefit besides charcoal and timber. Even though hectares of mangroves have been planted as an initiative to rectify the degraded areas, the degree of protection by certain coverage of mangroves remains lacking understanding. In Kedah, 8,322.79 ha of mangrove coverage was recorded in 2000 [11], which was alarmingly degrading over the decade with 7,841.25 ha remaining in 2012 [12]. Therefore, the alarming degradation rate indicates that proper study and management are vital to ensure that promising protection can be provided in the respective coastal area.

Assessment of the coverage and area of mangroves is necessary for planning and managing future disaster countermeasures. The affecting parameters such as geometries, widths, densities, and mangrove species as well as the conditions of the impacting waves are correlated in analyzing the optimum protection provided by mangroves. Thus, a profound understanding of the interaction between mangrove characteristics and wave conditions lead to the achievement of the purpose of this study.

1.4 Objectives

The main objectives to be achieved in this study are as follows:

1. To analyze the distribution and characteristics of mangrove along the Kedah coastline.
2. To determine the wave height reduction across the mangrove forests along the Kedah coastline.
3. To determine the adequacy of mangrove band width for optimal protection along the Kedah coastline using Bao's formula.

1.5 Scope of the Study

The scope covered in this study incorporates the relationship between mangrove characteristics and coverage, with wave conditions along the coastline of Kedah. The study comprises field assessment, remote sensing, as well as Geographic Information System (GIS) analysis and wave analysis. Eight study areas stretching along five districts in mainland Kedah and Langkawi Island were selected for field assessments including Kota Kuala Muda, Merbok, Sungai Daun, Kangkong, Kuala Kedah, Jerlun, Sungai Melaka, and Kuala Teriang.

The determination of mangrove characteristics and distribution encompasses the band widths, densities, geometries, and mangrove species. Prior to that, field assessments were conducted to acquire sufficient data for these parameters. Next, remote sensing and GIS tools were adopted to model mangrove mapping. These advanced geospatial technologies were deemed reliable in the identification process, mapping the coverage areas and distribution of mangroves at the targeted study site, Kedah.

Since wave conditions also govern the adequacy of mangrove performance in dissipating wave, secondary wave data such as the significant wave height, peak wave period, and wave directions were obtained from the Department of Irrigation and Drainage (DID) Malaysia. Several wave analyses were considered including wave reduction and wave transformation. Adequacy of mangroves, which depends on the interaction of both mangrove characteristics and wave conditions, was later assessed.

The output from the study is expected to benefit the Forestry Department, coastal planners and policy makers as guidance in managing the current mangrove coverage, planning for rehabilitation in the degraded mangrove areas, and designing protection measures. Besides, the implementation of the right replantation strategy and technique by the Department of Irrigation and Drainage is achievable with the analysis of mangroves and waves. This replantation will eventually be beneficial to the surrounding coastal communities in safeguarding the coastline from wave attacks.

1.6 Limitation of the Study

Wave dissipation is mainly resulted from the drag force and bottom friction. Drag force is caused by the structures of the mangrove, including the roots, trunks, and canopy. Meanwhile, bottom friction occurs due to the seabed roughness. Both frictional drag forces impose resistance to the incoming wave and affect in energy dissipation that subsequently contributed to reduction of wave height. The bed friction might not be adequate to cause net dissipation, thereby drag force serves by the mangrove is important to enhance the attenuation rate [13]. This is supported by [14, 15] which claimed that vegetation drag force is the dominant force causing the attenuation in wave.

Wave reduction due to bottom friction in a large water depth is inefficient, as reported by [16]. In their study, it was observed that only 5% of wave dissipated over 100 m forest, in the absence of mangrove with 2.0 m water depth. In the case of 0.2 m water depth, the dissipation was marked as 20% over the similar width into the forest. An interpolation was then made to observe the water depth of the studied area in Kedah which indicated that the wave reduction caused by bottom friction was only 13%. Thus, considering the minor effect from the muddy seabed roughness, the bottom friction was not addressed in the calculation of wave dissipation for this study. Although numerous studies have recognized the role of bottom friction in mangrove-induced wave dissipation, but some are neglected this parameter in their calculation and mainly focused on mangrove drag friction only [9, 17, 18].

Secondly, the selection of Bao’s formula instead of other available formulas discussed in the literature review. Similar to other location-based or site-specific formulas presented in the literature review, Bao’s formula is an empirical formula based on the Vietnamese coast. However, the limitation with Bao’s method is that it takes an over-conservative value of the mangrove structures, for instance, the average tree height and the canopy closure percentage, and did not break or delineate the differentiation of the species itself. Besides, this analysis fails to incorporate any worst-case scenarios such as high tides at night or storm where wave heights could reach 3 m or more.

Nonetheless, Bao has been successful in proving the high accuracy of the theoretical value for the wave height reduction with the experimental value obtained from the Vietnam coastline. In general, Bao's formula considers all affecting dissipation factors in generating its formula, while the other formulas are only focused on a few factors alone such as density, band width, mangrove structures, and many more. Furthermore, some required parameters in other formulas were unavailable and could not be processed during the study; hence, this contributes to another constraint in applying the other formulas.

Another shortcoming includes the processing of spatial mangrove mapping, for instance, the selection of medium resolution images instead of the higher resolution satellite images. While a high-resolution image might produce better accuracy during the classification process, the medium-resolution image was rather utilized in producing the mangrove distribution map in Kedah due to budget constraints. In addition, as a result of the unavailability of the right tools, mangrove height could only be measured using the scaling method, whereby the measuring tape could only measure the height within the reachable height of the researcher.

1.7 Significance of the Study

The role of mangroves as the first line of coastal protection has captured more attention in many countries nowadays and become a significant point that leads to various replantation initiatives. In conjunction with that, one of the main outputs gained from this study was to come up with an optimum replantation area at the required coastline in Kedah. This is to ensure that these mangroves will provide sufficient protection to the coastline from the prevailing wave attack. Thus, a deep understanding of the current coverage of mangroves as well as wave conditions impacting the coastline and their interactions are needed in order to serve the focus of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Chapter 2 presents an extensive literature review related to the wave dissipation performance of mangroves. This chapter begins with the background of mangroves, their functions and benefits to the surrounding communities, their defense ability, as well as their coverage on the global and national scales. As the chapter progresses, more specific literature on the mangrove dissipation mechanism is discussed along with the previous studies assessing a similar scope through various approaches such as field studies, laboratory tests, and numerical modelling. The driving factors affecting dissipation performance, from mangrove parameters to hydraulic parameters and other factors are described. Some literature on the Geographic Information System and remote sensing, especially their usage will also be reviewed in this chapter.

2.2 Mangrove: A Unique Ecosystem

Mangroves are attributed to special features that enable them to survive in harsh habitat condition as well as adapting to extreme tide exposures and high salinity in the coastlines [19]. The saltwater tolerant ability of these tidal habitat vegetations enables them to colonize in the intertidal regions. Mangroves usually grow above the mean sea levels and below the highest tidal levels [20]. Typically, mangroves have special bark and leaf structures with tough root systems that stick up in the air to ensure that the plants can breathe. Moreover, a great distinction between mangroves and normal trees comes from the aerial and prop roots found in mangroves.

Complex and impressive aboveground aerial and prop roots aid in oxygen uptake and provide physical stabilization in the soft sediment and mudflat area. The roots of mangroves also act as wave breaker that provides buffering functions to the coastal properties from the turbulent kinetic energy of waves. In addition, the roots promote the accumulation of sediment [21] that helps in land-building and surface elevation [22]. The viviparous propagules offer quick establishment to the parent trees or float away until it thrives somewhere in new areas.

Four main species of mangroves that are dominantly found in Malaysia, namely *Rhizophora*, *Bruguiera*, *Sonneratia* and *Avicennia*. They are easily recognized and differentiated by their root configurations. *Rhizophora* has stilt roots, while *Avicennia*, *Sonneratia*, and *Bruguiera* have pencil-like, cone-like and knee roots [23, 24, 25, 3], respectively (see Figure 2.1).

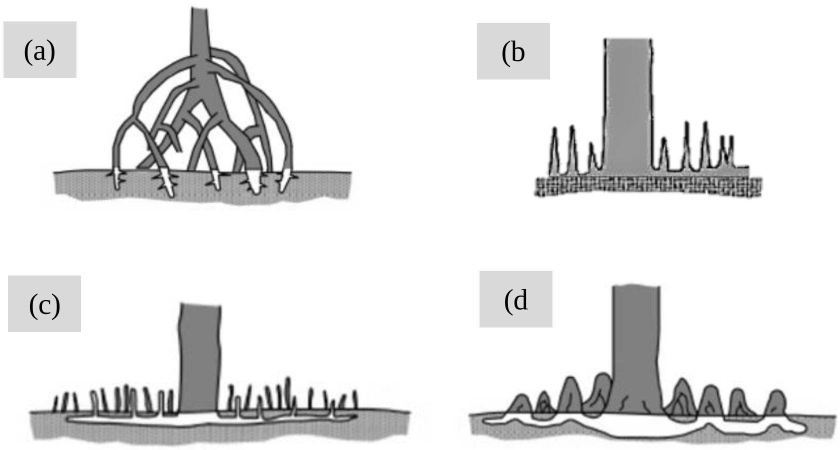


Figure 2.1: Roots of (a). Rhizophora, (b). Avicennia, (c). Sonneratia, and (d). Bruguiera [9]

2.2.1 Mangrove Benefits and Functions

Mangrove forests deliver numerous important goods and services that are essential to human populations and the surrounding ecosystem. The services that mangroves offer include provisioning, regulating, protecting, and supporting. Mangroves provide provisioning services with the supply of food, fuel wood, and timber [26]. Through regulating services, they further help in flood control, pollution control, and biological regulation. Besides that, their fundamental role in providing protection from coastal erosion, flooding, and storm are widely known. Shore stabilization and nutrient cycling are also among the supporting services that mangroves provide.

Mangroves play a crucial role in the coastal ecosystems as a food chain. Aquatic species such as shellfish and finfish are supported by mangrove-derived materials for food [27]. According to Rog, Clarke, and Cook [28], the mangrove ecosystem is also vital to terrestrial vertebrates through the procurement of important ecological processes such as mangrove pollination and mineral exchange. Based on their studies, 88% of mangroves benefited the marine organisms through feeding.

Additionally, mangroves provide local livelihood with various commodities such as charcoal, fuel, wood as architectural and infrastructure timbers, fishery, medical uses, and salt processing [29]. The woods are high in commercial value [5]. Based on a previous study by Lang and Kairo [30], mangroves in Kenya were utilized for various constructions depending on the grade of poles. The plants selected for fuelwood include *Aegiceras corniculatum*, *Sonneratia*, *Avicennia*, *Heriteria* species, and *Excoecaria agallocha*. *Phoenix paludosa* is also regularly used as a household material [31].

Globally, the mangrove ecosystem contributes to human activities [32, 33, 34], mainly in a diverse variety of fisheries (seaweeds, fish, crabs, prawns, mollusks, and other invertebrates) and manufactured goods (timber, fuel, corks for dyes, and food). Mangrove trees can also grow to large sizes and be more valuable in the construction sector that is always used as furniture piling, flooring, bridge, cottage, and stairs.

Nonetheless, the benefits of mangroves are not limited to metropolitan centers alone but also in locations with lesser populations. The vast coverage of mangroves colonizing Pulau Kukup, Malaysia, an uninhabited island, supports the important regulation services for flood control and protection from storm events and coastal erosion [35]. From a global perspective, mangroves are also significant in protecting several coastal cities and regions with more than 150,000 people from flooding every year in Lagos, West Africa, Karachi in South Asia, and Wenzhou in East Asia [36].

The complicated and dense aerial roots protect the soil of intertidal zones, reduce erosions, and preserve sediments mostly for stems, trunks, and canopies, which is also effective in dissipating coastal flooding and wave against flooding [37, 38, 3]. Mangroves also serve as sinks for carbon in biological regulation service by trapping the deadwood deposition and sediments delivered from the uplands [35] aside from trapping litters and floating marine debris that is transported away by tides [39, 40].

Mangroves facilitate in maintaining biodiversity, particularly in protecting the juvenile fish from larger fish and birds habituating the ecosystems. Apart from providing a home to an array of marine species, mangroves also act as a breeding, spawning, and nursing ground for marine life and its communities [41]. The lack of food sources and smaller habitat size associated with mangrove destruction may result in lower fish populations. As such, mangrove roots systems are crucial to protect and raise young aquatic species such as fish, prawns, and crabs [25, 42].

Through their supporting services, mangroves further assist in soil formation and shoreline stabilization [43, 44, 45]. Sungai Pulai in Johor, Malaysia is critical for stabilizing the shoreline and restricting storms and tidal devastation. Thus, the mangroves along Tanjung Piai reduce potential sediments from penetrating the reservoirs and help control the coastline against elevated storm surges [35]. Mangroves also promote coastal stabilization by increasing sediment accretion [46] and decreasing the carrying capacity of sediment by waves [47]. Many coastal species and roots systems can overcome coastline depletion by expanding sediment growth.

Another service provided by mangrove is cultural service, which includes recreational [48, 49], eco-tourism [50, 51], educational, and research purposes. Mangrove-based ecotourism has become a pivotal point for mangroves to be acknowledged by communities. The construction of observation decks and boardwalks also helps tourists to explore and see mangroves from a nearer distance. Likewise, boat touring enables tourists to experience the mangrove ecosystem better. Besides, other uses of mangrove forest are for handicraft and decoration purposes, which can potentially enter the market value that brings benefits to the local communities [52].

2.2.2 Mangroves as Coastal Buffer

Mangroves, standing as the first line of the coastal buffer, play a significant role in diminishing the severe effects of wave actions against the coastline [53, 54, 55]. Mangroves are acknowledged for their ability to dissipate wave energy [56], thus creating shoreline stabilization and storm-protecting surroundings [4]. The protection function that mangroves provide is not only relevant for tsunamis but including other natural calamities such as storm surges and cyclones [26, 44], where the areas with mangrove were reportedly less damaged compared to mangrove-free areas [57].

Burger [58] studied the correlation among the critical factors in the attenuation process and summarized that wave dissipation highly depends on both mangrove structures and hydraulics parameters. Aside from that, mangroves also demonstrated a capability in wind buffering. McIvor et al. [13] concluded that 100 m of mangroves could mitigate the intensity of wind and surge waves with a peak discharge of less than 70 cm between 13% and 66%. Besides, a declining pattern in severe storm surge water levels over mangroves from 5 cm to 50 cm per kilometer was observed. One kilometer of mangrove forests is required to counter surface wind waves by more than 75% [59].

The 1996 tropical cyclone 07B of estimated peak winds at 115 kt (59 m s^{-1}) remarks the vulnerable impacts to the local inhabitants in west coast of India. As reported, the cyclone led to occurrence of massive flooding, with at least 10,000 homes were collapsed, sinking of ferry resulting to lost of 42 passengers, and more than 1,000 fishermen were missing at sea [60]. Nonetheless, interview with the coastal communities highlighted that the areas with healthy mangrove forests were saved from the devastated cyclone, whilst the adjacent shrimp pond (previously was mangroves area) encountered the consequences of cyclone and flooding [41].

The 2004 IOT tragedy also proved that the villages shielded by the mangroves were protected [61] and experienced minimal destruction compared to the barely exposed villages without mangrove protection [62]. The tsunami with magnitude of 9.1 travels at 500 m h^{-1} [63]. In Sri Lankan village, only two death tolls recorded in the densely populated mangroves areas, but 6,000 people were found dead in area with no mangrove’s protection [64]. Even though mangroves might not completely protect an area from the destruction of high tsunami waves, the damages might be significantly reduced when the areas are buffered by mangroves.

Nagapattinam, Kanyakumari, Chennai and Pondichery, India, which initially were populated by a high density of mangroves; however, due to overexploitation, the region encountered maximum damages during the 2004 IOT disaster [26]. According to Sarkar et al. too [26], in 1999 when Super Cyclone that moved with wind speed peak at 260-270 km h^{-1} [65] hit Bhitarkanika and Orissa, India, the vast presence of mangrove forests extensively spared the fury of the cyclone. Human casualties were recorded in all tahasils (referring to local administrative units under a district) of Kendrapada district, Orissa, except Rajkanika which is sheltered by the well-preserved mangrove forests of Rajnagar tahasil [57].

Likewise, the wind speed reduced by 20 km h^{-1} by the Sundarbans mangroves in India and Bangladesh during the 2019 Cyclone Bulbul [66]. The world's largest mangrove forest saved the Sundarbans from the cyclone of wind speed reached up to 130 km h^{-1}. Numerical simulations conducted after the 2005 Hurricane Wilma in Gulf Coast of South Florida indicating that the inundation area affected by Wilma would extend beyond 70% inland in the mangrove-free area [67]. When the 2013 Super Typhoon Haiyan occurred in Leyte, Philippines, the buffering capability of mangroves was again emphasized when mangroves planted a few hundred meters from the shoreline defended the full impact of the waves [67].

2.2.3 Global and National Mangrove Distribution

Mangrove coverage and distribution are briefly described in the following sections on global and national scales, accordingly.

2.2.3.1 Global Mangrove Distribution

Hamilton and Casey [68] reported that 8,349,500 ha of mangroves occupy every continent across the globe. However, the status was found to be declining from 18,100,000 ha in 1996 [69], 13,776,000 ha (Figure 2.2) in 2000 [19] and 15,2000,000 ha (Figure 2.3) in 2005 [70]. Commonly occurring in the tropics, subtropics, and temperate regions, this vegetation sprawls in 112 countries [70, 71]. This slightly contrasts with the finding by [19] that mangroves exist in 118 countries in their remote sensing-based work. However, both were lower than 124 countries as mentioned by [70].

Asia globally dominated the highest extent of mangrove coverage by 42%, followed by Africa, North and Central America, Oceania, and South America with 20%, 15%, 12%, and 11% respectively (refer Figure 2.2(a)). Figure 2.2 (b) depicts mangrove distribution in Asia, with Indonesia remaining as the vast stretched location in Southeast Asia and the world with coverage of 3,112,989 ha [19]. Moreover, Southeast Asia has the richest mangrove species diversity on a worldwide scale [70, 71].

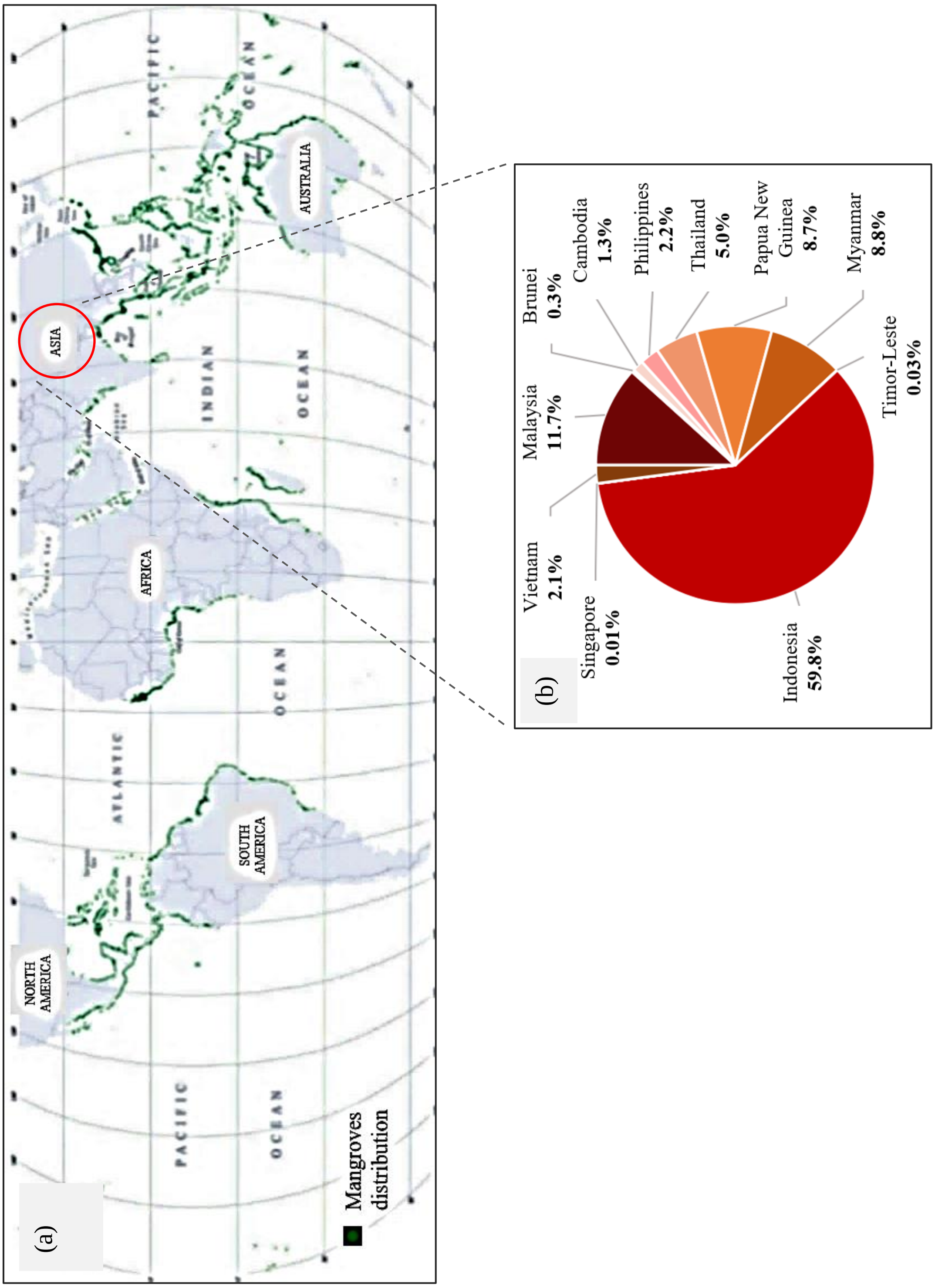


Figure 2.2: (a) Global mangrove distribution in 2000 [19] (b) Mangrove distribution in Asia

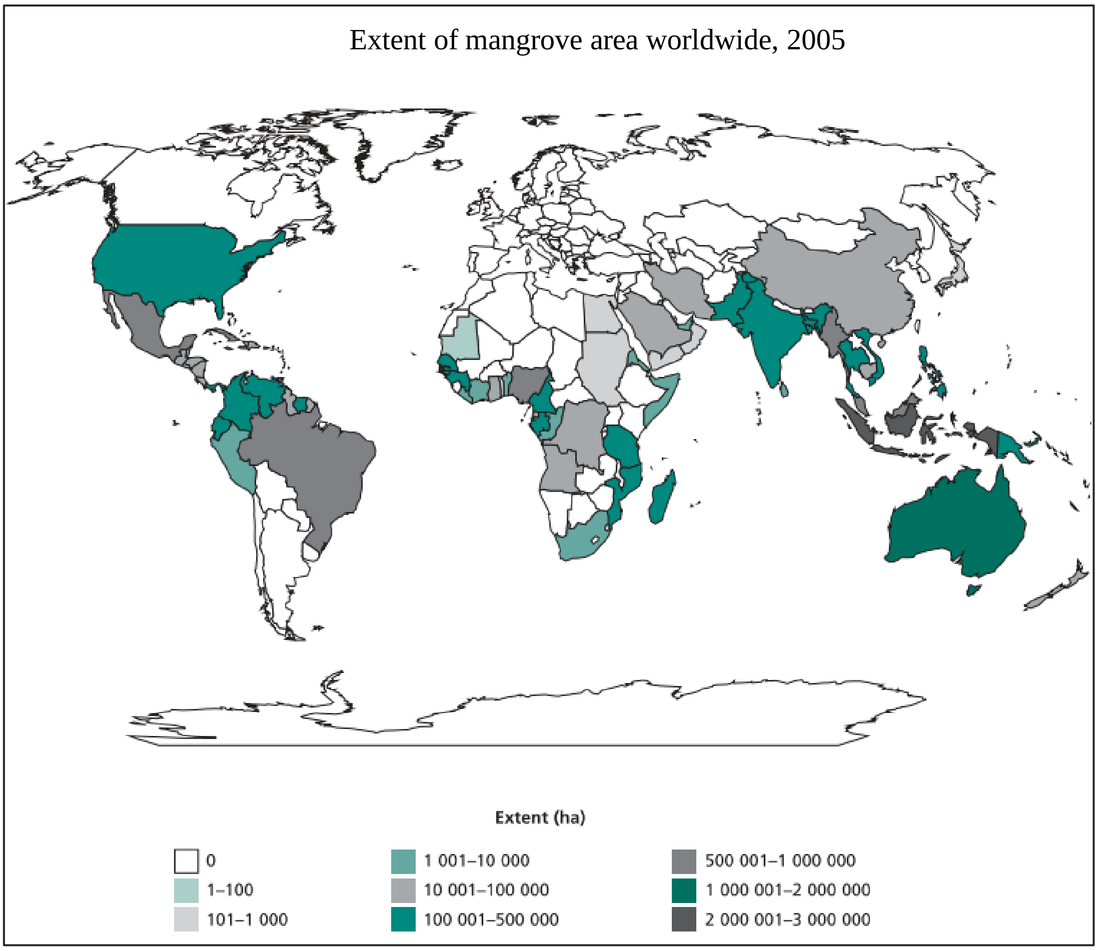


Figure 2.3: Global mangrove distribution in 2005 [70]

However, the highest demand for mangrove products in the construction sector and fuel has contributed to the loss and depletion of mangrove forests. For instance, between 1980 and 2005, almost 20% of mangrove areas have been degraded. As stated by Basha [72], 35% of global mangroves have been lost in the last two decades. Recently, the worldwide mangrove degradation rate has also been estimated to range from 0.6% to 0.39% per year.

2.2.3.2 National Mangrove Distribution

Malaysia has among the largest tract of mangroves in Southeast Asia. The country was ranked sixth with the highest population of mangroves in the world and second highest in Asia after Indonesia with 3.7% of the total global mangrove cover [19, 70]. Besides, as reported in a study by [72], Malaysia encompassed 11.7% of mangroves in Southeast Asia. Sabah accounted for 60% of the nation's total mangroves and marked with the highest distribution. 22% of mangroves were also found covering Sarawak with another 18% in Peninsular Malaysia [4], while [73] estimated about 61.6%, 16.5%, and 21.9% of mangroves in Sabah, Sarawak, and Peninsular Malaysia, respectively. The detailed distribution of each state as of 2012 is tabulated in Table 2.1.

Table 2.1: Mangrove coverage in Malaysia [12]

State	Total area (ha)
Johor	27,343
Kedah	6,201
Kelantan	744
Melaka	80
Negeri Sembilan	204
Pahang	4,266
Pulau Pinang	773
Perak	42,269
Perlis	13
Selangor	19,547
Terengganu	1,987
Sabah	378,195*
Sarawak	139,890*

*Updated from [4]

In Peninsular Malaysia, mangroves are distributed largely on the west coast (including Perak, Kedah, and Selangor) rather than the east coast [74]. This is due to the sheltered conditions on the west coast that promote sediment settlement and, thus, increasing mangrove occurrences [2]. Additionally, a widespread extent was found in the coast of Perak, which represents the largest extent and followed by Johor as the second-dominant coverage, while Perlis has the lowest extent.

Matang Mangrove Forest in Perak is the largest mangrove forest in Malaysia [5, 12, 75] that occupies an area of 40,000 ha. This location is known as a permanent forest reserve in 1904, with attempts to conserve the forest history in 1902 as the earliest mangrove reserve in Malaysia. This location is also well-known as the best-managed forest [70]. Additionally, the three protected forest reserves in Sabah include Trusan Kinabatangan Forest Reserve, Kuala Maruap and Kuala Segama Forest Reserve, while Kulamba Wildlife Reserve is the largest mangrove forest in Malaysia with 78,000 ha.

2.3 Mangrove Roles in Wave Dissipation

Mangroves are considered as an eco-defence alternative, which is more preferred than the hard engineering structures in breaking waves and withstanding the coastline from future erosions. The coastal structures might impose some adverse effects on the coastal ecosystems, especially if not maintained. Hence, mangroves as a nature-based solution are opted in providing the same protective function as some other structures.

Mangrove functionality in dissipating waves is well-known. As waves propagate into the mangrove forest, the geometries of mangroves such as trunks, roots, and, in some cases, canopies will act as the friction drag that slows down wave motions and reduces the amplitude of the waves [76, 77, 78]. In consequence, the waves lose some part of their energy and wave dissipation occurs. A low magnitude of dissipated waves further minimizes erosion in the coastal area resulting from the severe waves.

As waves passed through the forest, the incident wave height reduced due to seabed friction and resistance from mangroves, as explained in Figure 2.4. The reduction rate (r) of waves is defined as the difference between the heights of incident waves (H_i) and transmitted waves (H_t) over the distance travelled into the mangrove forest.

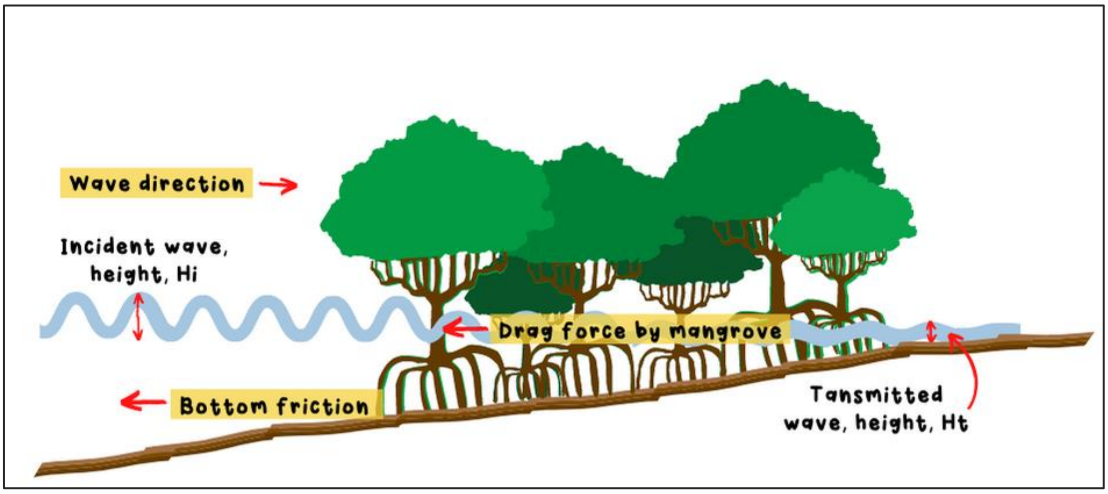


Figure 2.4: Wave and mangrove interaction

Mazda et al. [16] developed an equation to show the rate of reduction:

$$r = -\frac{\Delta H}{H} \cdot \frac{1}{\Delta x} \qquad \text{Equation 2.1}$$

Where r is the wave height reduction rate per unit distance (m^{-1}), ΔH is the reduction in incident wave height, H is the incident wave height, and Δx is the distance travelled over the mangroves. Rasmeemasmuang and Sasaki [79] also introduced the reduction rate coefficient to demonstrate the dissipation rate of waves.

$$R(\%) = \frac{H_i - H_t}{H_i}\ x\ 100 \qquad \text{Equation 2.2}$$

Where R is the coefficient of wave reduction (%), H_i is the incident wave height (m), and H_t is the transmitted wave height (m). Equation 2.1 includes the distance or width of mangroves in the equation, whereas Equation 2.2 only addresses wave reduction.

2.3.1 Studies on Wave Dissipation by Mangroves

Numerous studies have been conducted over the decade in discussing the interaction of incoming waves that propagate into mangroves. Although the scientific studies adopted different methods and strategies, the dissipation function of mangroves remains evident. Generally, these methods include field observations, numerical modeling, and experimental tests.

2.3.1.1 Field Observations on Wave Dissipation by Mangroves

Wave dissipation analysis by field observation has been widely conducted; however, this method is mostly integrated with numerical modelling and analysis. For instance, the differences in wave reduction over a vegetated area and unvegetated mudflat area were discussed by [76]. Two sites in the Red River Delta, Vietnam, one with mangroves and the other is a bare mudflat area, were assessed to clarify mangrove functions as wave height reduction and dissipation factors. The mudflat thrived by mangroves resulted in a greater drag force. The dense structures of the mangroves, thus, increased the friction and eventually caused more wave energy to be dissipated.

As seen in Figure 2.5, the mangrove area depicted a greater wave reduction and resistance coefficient compared to the other two. Aside from that, the coarser sandy-covered mudflat surface (referred to as beach plain) gave more friction towards the waves, hence resulting in a higher dissipation and resistance coefficient than the mudflat area, which has a finer surface. A drag force function of $0.6e^{0.15A}$ was obtained for the mangrove area, where A denotes the cross-sectional area. Meanwhile, for the mangrove-free area, the drag function was equal to 0.6.

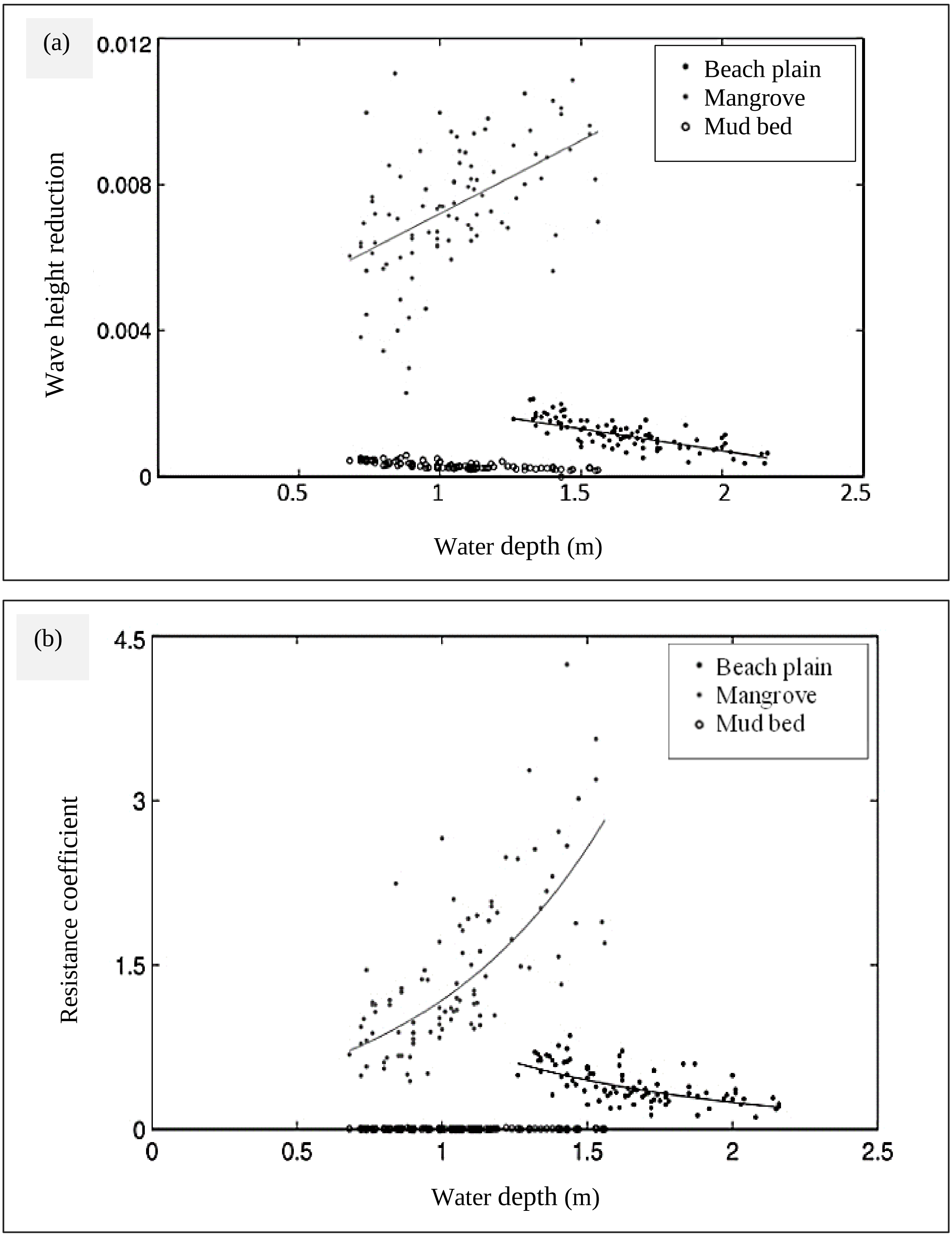


Figure 2.5: (a) Wave reduction vs water depth (b) resistance coefficient vs water depth [76]

A field observation by [16] studied the significant effect of mangroves in performing wave dissipation. The study also emphasized the effect of water depth on wave reduction in comparison with the reduction due to the bottom friction. In the areas dominated by mangroves, the reduction of waves was reportedly declining as the water depth increased with the highest magnitude of 0.006 m^{-1}. The rate of wave reduction in the mangrove-free area also decreased by 0.001 m^{-1} with the increase in water depth. This reported a contradict finding with Quartel et al. [76], in the relationship between the wave reduction and the water depth, where Mazda et al. [16] elaborated more rational and reasonable justifications.

Mazda et al. [16] added that the high wave reduction in the mangrove area was caused by the submerged roots of the mangroves that act as the friction drag. However, as the water depth increased, the reduction decreased due to the geometry of the roots tapping upwards and decreasing their diameter. This signifies less surface contact of roots with the water particle that eventually causes low attenuation. Meanwhile, the mangrove-free area was solely dependent on the bottom friction to dissipate the waves, hence resulting in a lower reduction rate.

Unlike the previous two studies that analyzed the common wind-induced sea waves dissipation, a study by Montgomery et al. [17] considered high-water events that included surges and tide conditions. Besides, the effect of channelization on attenuation was another factor incorporated in the study. Channelization refers to the presence of drainage channel in the mangrove area. However, the study found no attenuation of waves in the area with the drainage channel since the flowing water was diverted into the drainage before it was transported across the mangrove area. This explains that the mangroves in the area only played a minimal role in restricting the flow.

Meanwhile, in the non-channelized area, the contribution of the mangroves was clarified. The flood waves propagated slowly into the mangrove and a reduction ~24 cm/km of the tidal level was also recorded as the waves moved from the seaward to the landward station in the study area. Therefore, the water flow route also affected the reduced efficacy of mangroves.

In Jakarta, Indonesia, the waves dampened by mangroves, specifically the *Avicennia marina* species were studied [80]. Mangroves served as resistance as the waves moved into the forest and created drag. The relationship between mangrove width and wave energy was established as expressed in Equation 2.3:

$$Y(energy) = 0.003x^3 + 0.208x^2 - 4.620x + 40.29 \qquad \text{Equation 2.3}$$

Where Y is the attenuation energy ((m sec^{-1})^2/c 2 min^{-1}) and x is the thickness of the mangroves (m). Y indicates the amount of energy attenuated over x distances of the mangroves. Thus, the wider the mangrove width, the more wave energy gets muted.

Another current study [81] with a similar objective was carried out in East Lampung Regency, Indonesia. An additional wave measurement equipment was installed in the field colonized with *Avicennia marina* species. The attenuation factor presented by ΔH shows the difference in wave heights before and after entering the mangrove forest. The dissipation upon different thickness or mangrove width can be observed using the following Equation 2.4:

$$\Delta H = -0.022x^2 + 0.259x + 0.393 \qquad \text{Equation 2.4}$$

Where ΔH is the wave energy attenuation (m) and x is the mangrove thickness (m). However, both studies only addressed the width of mangroves as the factor reducing the waves. Mangrove geometries, distribution, and species composition were also measured and observed; however, none of the data was emphasized in the discussion and considered in the formula.

Additionally, the roots and trunks of mangroves contributed to the dissipation factor. A field study on this parameter, as discussed by [82], revealed that wave attenuation increases with the increase in the mangrove width. However, in this study, the observed waves were not attributed to the wind-induced waves from the sea but rather the waves generated by the fishing boats passing the channel. The wave attenuation over different widths was formulated in Equation 2.5:

$$y = 0.5233x + 7.5497 \qquad \text{Equation 2.5}$$

Where y is the average wave reduction (%) and x is the plot/distance inside the mangrove forest (m). Figure 2.6 indicates the data of wave reduction over the respective distance from the edge of the mangroves. The reduction shows an increment as the waves propagated further into the mangrove forest.

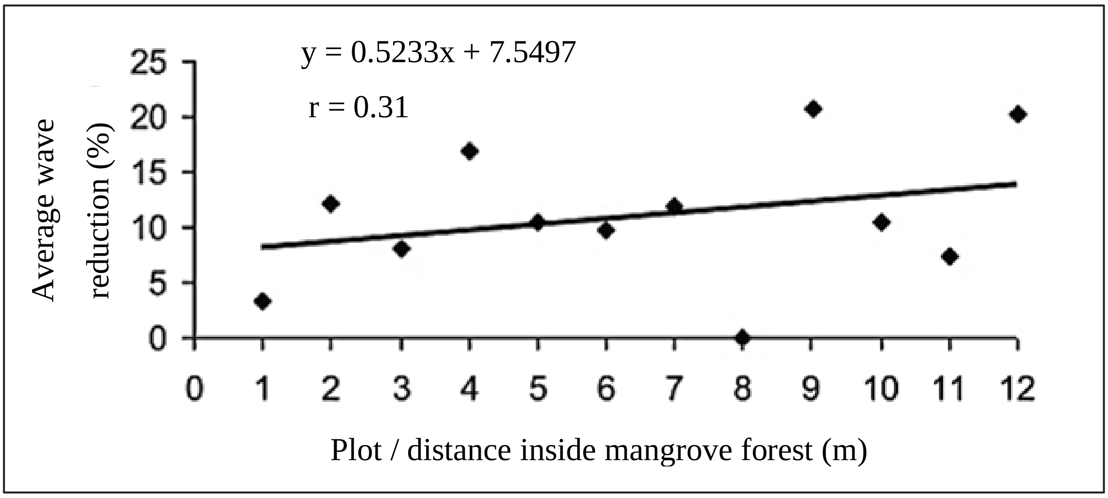


Figure 2.6: Average wave reduction vs distance inside mangroves [82]

Rhizophora species was experimented [83] for its wave dissipation performance, which resulted in 57.73% of waves being attenuated. The dissipation was investigated at certain porosity of the mangrove forest, which corresponds to the volume with no existence of roots or trunks on the surface. Thus, porosity and wave steepness were used in the determination of the transmission coefficient as shown in Equation 2.6.

$$K_t = 1 - \left\{ e^{0.836} \left(\frac{H_i}{gT_i^2} \right)^{0.771} N_p^{-55.990} \right\} \qquad \text{Equation 2.6}$$

Where K_t is the transmission coefficient, H_i is the incident wave height (m), g is the acceleration (m/s^2), T_i is the wave period (s), and N_p is the porosity value. The results revealed an inverse relationship between the transmission coefficient with the porosity and the wave steepness.

A study by [8] has shown the relations of mangrove geometries, mangrove band widths, and wave heights in analyzing wave attenuation. Mangrove geometries denote the diameter at breast height (DBH), height, tree density, canopy closure, and species. As depicted in Figure 2.7, the wave heights showed a significant relationship with the mangrove band widths. An exponential decrease was observed with the increase in mangrove band widths. The relationship between wave dissipation and mangrove geometries is explained in Equation 2.7 (also known as Bao's formula):

$$W_h = (0.9899 \times I_{wh} + 0.3526) \times e^{(0.048 - 0.0016 \times H - 0.00178 \times ln(N) - 0.0077 \times ln(CC) \times B_w)}$$

Equation 2.7

Where W_h is the sea wave height behind the forest band (cm), I_{wh} is the initial sea wave height (cm), H is the average tree height (m), N is the tree density (tree ha^{-1}), CC is the canopy closure (%), and B_w is the forest band width (m).

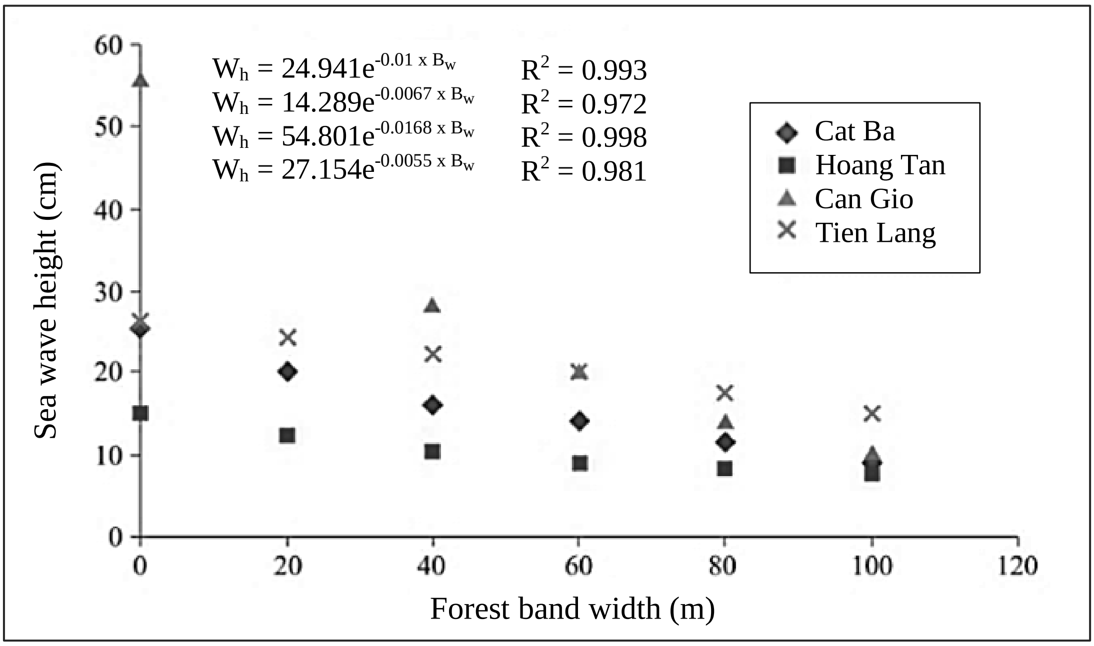


Figure 2.7: Sea wave heights vs mangrove band widths [8]

While the other equations focused only on the width of mangroves (Equation 2.3 – 2.5) or limited to certain species of mangroves (Equation 2.6), Bao encompassed the other driving factors in their formula which is valid to all species. Thus, this study is more relevant and applicable to all cases since most of the affecting factors including mangrove and wave parameters were considered in obtaining the equation, compared to the previously discussed studies that incorporated only a single or several parameters. A thorough analysis with comprehensive variables making the equation more reliable in assessing the wave dissipation performance of mangrove.

2.3.1.2 Numerical Modeling of Wave Dissipation by Mangroves

In recent years, simulation approaches using numerical wave models in studying wave dissipation are getting wider. Different types of numerical models have been extended and simulated to incorporate the effect of mangrove vegetation in dampening wave heights and energy. The Simulating WAves Nearshore (SWAN) model is among the widely used models in mangrove and coastal studies [84, 85, 86].

The SWAN model was adopted to study the dissipation characteristics of waves by four different mangrove species overgrown in two different salinity zonations such as hypo saline and hyper saline [87]. Comparisons were made between the wave heights with and without mangroves and mud input in both hypo and hyper saline stations. The magnitude of wave dissipation was observed to be greater in hypo saline than in hyper saline stations. However, the higher attenuation was not due to the salinity condition but was rather closely related to the high mangrove vegetation in the station.

Other than that, the authors also found that the hyper saline station was occupied by the *Avicennia* species, including *Avicennia marina*, *Avicennia alba*, and *Avicennia officinalis*, while *Sonneratia apetala* prefers to thrive in the low saline environment. This is parallel to the finding reported by [74], which revealed that the *Sonneratia* species is found to be grown in low-medium salinity, whereas *Avicennia* mostly occurs in high salinity conditions. This further evidenced that mangroves grow in their own zonations according to the adaptability of their species.

Adytia and Husrin [88] described a simulation of mangrove attenuation capability in dealing with tsunami waves. Optimized Variational Boussinesq Model (OVBM) was extended with additional dissipation term of bottom roughness in the equation. In the simulation, tsunami waves were represented by the non-breaking solitary waves. Only trunks and roots were taken into account in developing mangrove parameterization. Figure 2.8 illustrates that mangrove width with the same magnitude of incoming wavelength (B≈λ_0) is required in order to dissipate half (A=50%) of the incoming wave height, whereas in order to fully dissipate (A=100%) the incoming waves, mangrove width with that is four times the wavelength is required.

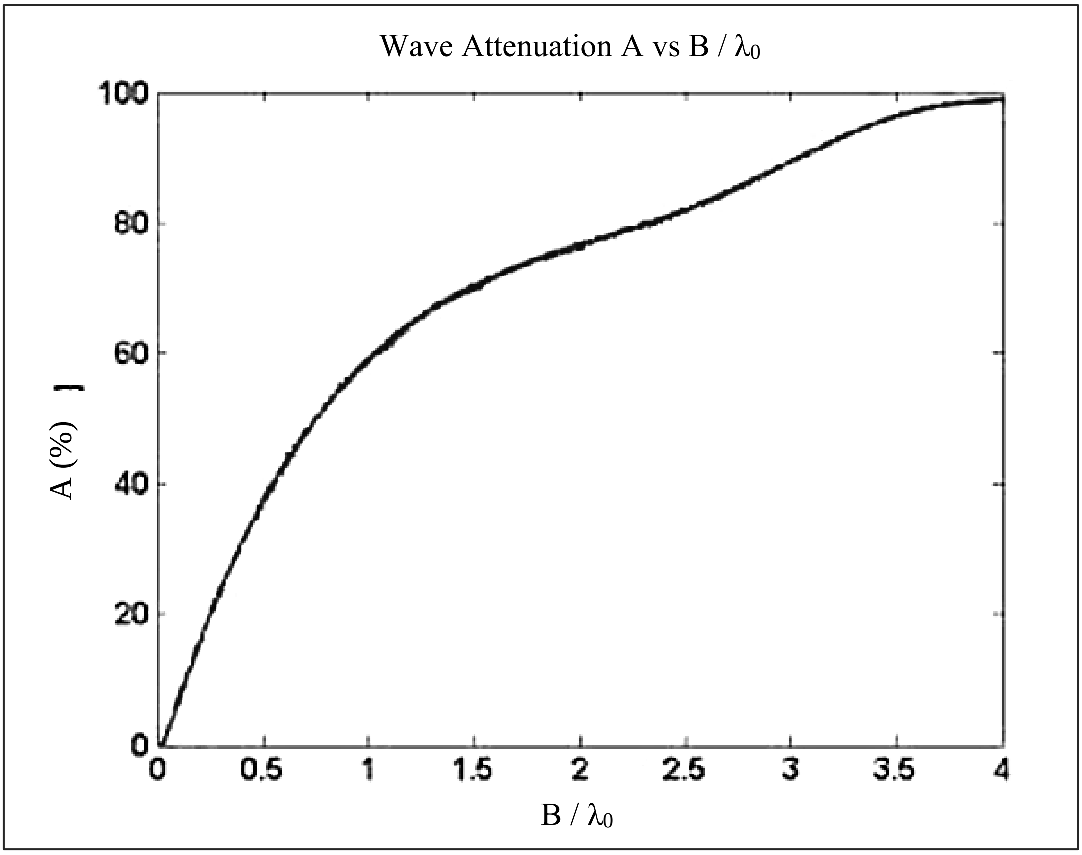


Figure 2.8: Wave dissipation (A) vs mangrove width (B) [88]

Numerical simulations on tsunami waves were also performed by Teh et al. [54]. Non-linear shallow water equation (NSWE) was used in simulating mangrove interaction on the hydrodynamics of tsunami in the modelling. The formulation of the Morison equation was extended in the momentum equation by incorporating a friction term representing mangroves acting as the friction towards the incoming wave actions. The modelling evidenced that wave heights and velocities can be reduced in the presence of mangroves. However, the degree of reduction varies significantly depending on several factors such as wave period and wavelength as well as mangrove characteristics including mangrove widths and densities.

The Morison-type equation has also been implemented in the XBeach modelling [89] by introducing the formulations for infragravity waves and mean flow. The wave dissipation effect of coastal vegetation formulation by Mendez and Losada [90] was also extended into the XBeach numerical model. The simulation generally studied coastal vegetation; however, it is still applicable to the complex vegetation species including mangroves and seagrass. Equation 2.8 below elaborates on the Morison-type equation adopted in this study:

$$K_v = \frac{H(x)}{H_0} = \frac{1}{1+\beta x} \qquad \text{Equation 2.8}$$

Where H(x) is the local wave height at a horizontal distance, x from the leading edge of the vegetation, H_o is the wave height at the leading edge of the vegetation, and β is a damping factor formulated using the linear wave theory. However, the bulk drag determination needs improvement by setting a constant value due to its uncertainty.

2.3.1.3 Laboratory Experiment on Wave Dissipation by Mangroves

Unlike field observation and numerical modelling, laboratory experiments assessing mangrove performance in attenuating waves remain limited. Moreover, most of the experiments on wave attenuation were mainly associated with coastal vegetation in general, rather than specifically by mangroves. However, the findings might still be relevant to this study. In laboratory experiments, the mangrove model was designed as a resemblance of the real mangrove structures or parameterization.

A study by [61] on a 50 m wide *Rhizophora* forest and bare land revealed that wave reduction by mangrove forest was almost half than by the bare land, contributing to a 52% and 29% reduction rate, respectively. The dissipation factor of wave on the bare land was only due to the bottom friction, while mangroves with a complex root system and trunk generate extra friction for a higher resistance towards the incoming waves.

Figure 2.9 indicates the relation between wave reduction over different widths of the mangroves in three cases: bare land, tandem, and staggered arrangement. The staggered order of mangrove models also showed a higher wave reduction compared to the tandem models, but with minimal difference. Hence, the arrangement in the mangrove forest was considered less significant in the attenuation process.

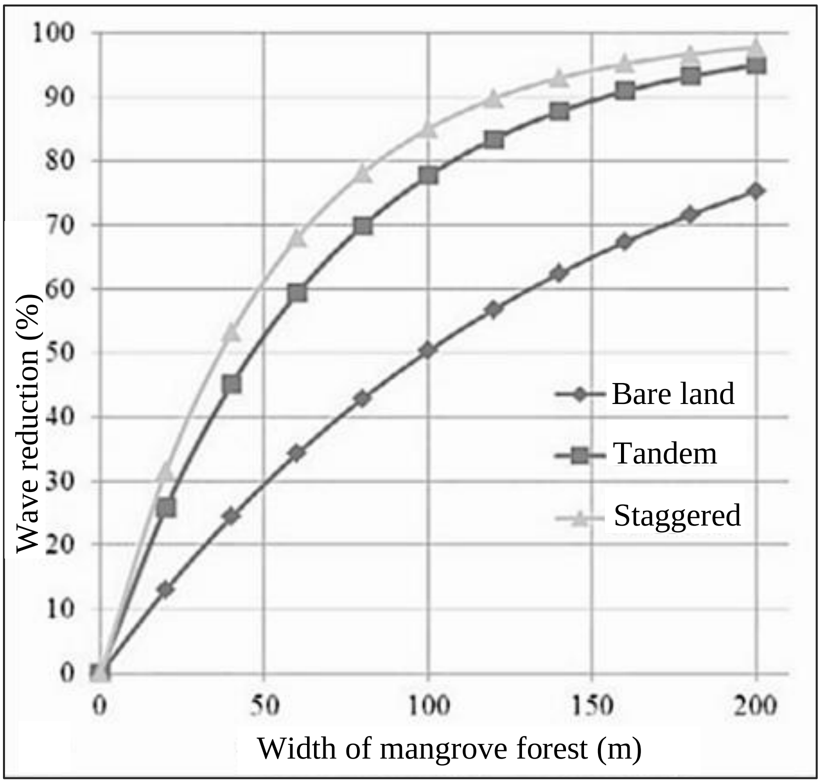


Figure 2.9: Wave reduction in bare land, tandem, and staggered mangrove models over different band widths [61]

Another experiment by [91] studied the influence of wave amplitude, wave period, as well as density of mangroves as the governing factors influencing wave dissipation rates. Based on the results, the highest dissipation of 64.55% was recorded over 1 tree/m^2 of mangrove density in submerged conditions, with a wave height and wave period of 0.15 m and 1.4 second, respectively.

Tsunami wave conditions have also been experimentally undertaken. For instance, [92] investigated mangrove dissipation performance under tsunami wave conditions, specifically on the *Rhizophora* species. Two tsunami flow conditions, solitary wave and tsunami bore were compared. The findings indicated that the tsunami bore condition imposed greater forces on the first row of the mangrove-parameterized model; however, the transmission rate in both conditions remained similar.

2.3.2 Factors Influencing Wave Reduction in Mangrove Forests

The sufficiency of mangroves to dissipate waves are subjected to several factors including mangrove characteristics and geometries, apart from wave parameters and other external factors such as bathymetry and water depth [43]. Figure 2.10 below depicts the relationship between the influencing factors and mangroves in depleting wave actions and energy. This is further detailed in Table 2.2.

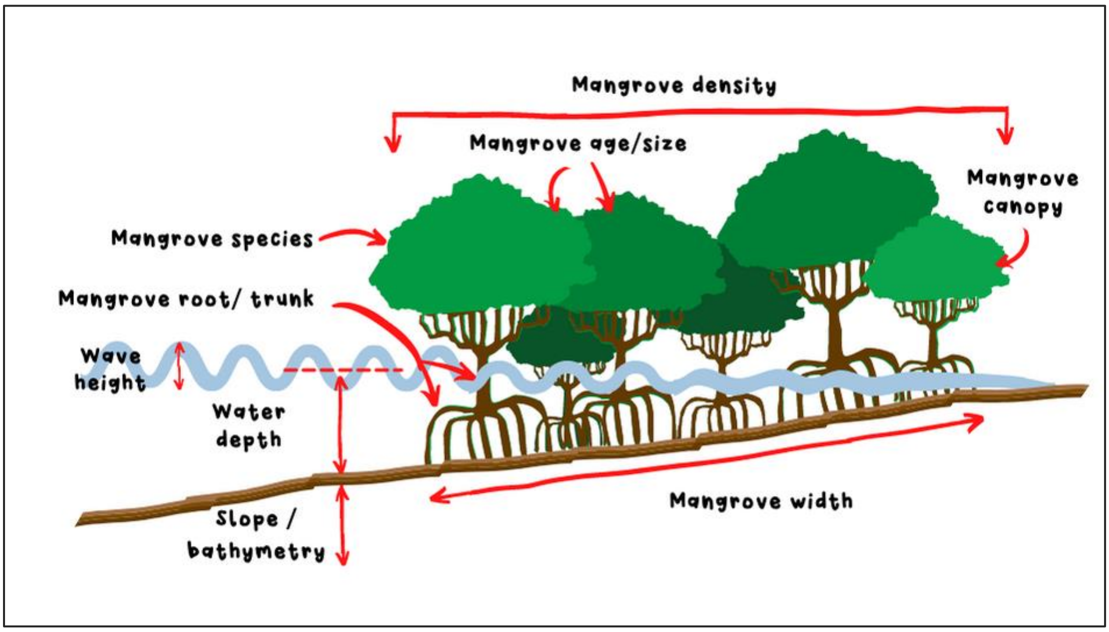


Figure 2.10: Influencing factors of wave attenuation in mangrove forests

Table 2.2: Factors affecting wave attenuation by mangroves

Factor		Description	Literature
Mangrove Characteristics	Width	Studies found that wave amplitude has an inverse relationship with the width of the mangrove forest. As the waves travel far into the mangrove trees, the height of the sea waves decays and, thus, attenuation increases. The narrow belt of mangroves might not be competent enough to withstand the large amplitude of waves and provide adequate protection to the coastal area. However, this still depends on other factors such as species, density, and other mangrove geometries in performing wave attenuation.	[81, 80, 8, 88, 9, 14]
	Density	Denser mangrove coverage dissipates more wave energy compared to mangroves with low density. In a dense forest, the dense network of roots and trunks over an area induces more drag force towards the waves that propagate between the smaller gaps. However, the forest with wide mangrove coverage but growing sparsely may not attenuate at a higher rate. Thus, greater density results in a greater dissipation rate.	[61, 93, 8, 76, 77, 87, 94]

Table 2.2: Factors affecting wave attenuation by mangroves (continued)

Factor		**Description**	**Literature**
Mangrove Characteristics	Species	Each species (including *Avicennia*, *Sonneratia*, *Rhizophora*, *Bruguiera*, etc.) performs differently due to different root configurations and trunks that each mangrove possesses, hence imposing a different dissipation rate. Rhizophora, among other species is claimed as the most effective in dissipating wave. The interlocking roots of Rhizophora limit the passes of the incoming waves across the mangrove forest and create more friction which further reduce the wave height. On another note, this also justifies that the right species of mangroves dominating the coastal area with adequate band width can effectively slow down the waves. More examples of wave reduction by different species are described in Table 2.4 below.	[16, 4, 95]
	Age	The age of mangrove represents the different sizes and diameters of mangrove geometries including the diameter of roots, trunks, and tree heights. Matured mangroves demonstrate better efficiency in dissipating waves due to their greater structure and firm roots. However, younger mangroves are less capable of withstanding strong wave actions and can easily be uprooted.	[61, 43, 62, 14, 96]

Table 2.2: Factors affecting wave attenuation by mangroves (continued)

Factor		Description	Literature
Mangrove Characteristics	Root	The root feature conveys a similar function as the trunks and leaves (or canopies) of mangroves, which acts as a shock absorber in reducing the magnitude and hydraulic forces of incoming waves. The root density in most mangrove species decreases with the increase in vertical layers. The high root density in the bottom layer contributes to additional friction and causes a high wave reduction rate. The drag force decreases with the increase in water depth when the roots taper off upwards, resulting in a decrease in the wave reduction rate. *Rhizophora* with a larger and complex root system can create greater friction compared to other mangrove species which have low root densities. While *Avicennia*, *Sonneratia* and *Bruguiera* have smaller spread and size of roots, Rhizophora possesses extensive root system elevated upwards that create less porosity to allow for wave to penetrate the mangrove forest.	[82, 16, 3, 77, 78]
	Canopy	Canopy denotes the spread of mangrove leaves. The thickly spread mangrove leaves form an obstruction to the water flow and dissipate the wave energy. However, the effect of mangrove canopies is only significant when the incoming waves reach the height of the mangrove canopies, which seems relevant to some high tide conditions and tsunami events.	[16, 97]

Table 2.2: Factors affecting wave attenuation by mangroves (continued)

Factor		Description	Literature
Wave Parameter	Wave Period	Mangroves are more effective in attenuating short period waves, compared to the longer ones. The transmission coefficient of the waves shows a linear increment relationship as the wave period increases.	[83, 54, 91]
Others	Water Depth	The wave energy depletion decreases when the water depth increases. Even though the roots generate considerable resistance, the decreasing density of the roots vertically decreases the wave reduction rate. In a greater water depth, the obstacles will have lower interaction with the flowing waves, causing minimal friction and drag effect and eventually less attenuation. Until the water level rises and reaches the thick mangrove leaves, the reduction rate will increase.	[76, 16, 13, 94]
	Bathymetry	Bathymetry is a factor that governs the water depth as well as the wave shoaling and breaking process. Mangroves, along with the potential to promote sediment accumulation, can help increase surface elevation. A steep slope will be created and therefore increasing wave shoaling and dissipation.	[13, 98, 97]

Table 2.3 elaborates on the reduction rates by different species of mangroves over different types of waves, mangrove densities, and widths. However, these studies are not comparable due to the different and additional parameters taken (e.g., consideration of mangrove age and bathymetry). Nonetheless, the dissipation performance of each type of mangrove can still be proven.

Table 2.3: Reduction rates by different mangrove species

Species	**Band Width (m)**	**Density (tree/m²)**	**Reduction Rate (%)**	**Literature**
Kandelia candel	100	Not provided	20	[93]
Rhizophora species	400	0.2	30	[99]
Rhizophora species	200	0.11(Sparse)	77	[94]
		0.16 (Medium)	86	
		0.22 (Dense)	88	
		0.36 (Super Dense)	91	
Rhizophora species	50	11 (Sparse)	65	[61]
		16 (Medium)	74	
		22 (Dense)	81	
Sonneratia species	100	0.08	50	[16]
Avicennia species	3, 5, 10, 20, 50	Not provided	60 - 98	[81]
Coastal tree model	100	0.3	50	[16]
Coastal tree model	100	0.3	90	[100]

2.3.3 Case Studies on Mangrove Adequacy in Dissipating Waves

Although studies on the wave dissipation effectiveness of mangroves are numerous, studies focusing on their adequacy in dissipating waves are, however, very limited.

2.3.3.1 Mangrove Adequacy Assessment in Vietnam

Studies on mangrove performance towards wave dissipation in coastal Vietnam has been briefly discussed in Sub-section 2.3.1.1. Apart from the attenuation assessment, Bao [8] had also assessed mangrove adequacy in dissipating waves and determined the minimum required mangrove band width for enough protection by deriving Equation 2.7. Next, a maximum wave height of 3 m with a safe wave height behind mangrove of 0.3 m was included in the minimum band width equation, expressing the vegetation structure index as V index. V index denotes the mangrove properties such as density, height of tree, canopy closure etc.

It was revealed that the V index was related to the required mangrove band width, where the required mangrove band width decays exponentially with the V index. In other words, high V index leads to narrower required band width and vice versa. Mangrove structures at each six (6) studied location were later assessed with the V index to identify the protection levels. The V index was further classified into five (5) prevention levels based on its relation to the wave heights, as tabulated in Table 2.4.

Table 2.4: Classification of protection levels [8]

Levels	**V index**	**Required band width [m]**	**Protection level**
I	< 0.005	> 240	Very weak protection
II	0.005 - 0.010	120 -240	Weak protection
III	0.010 - 0.015	80 - 120	Moderate protection
IV	0.015 - 0.028	40 - 80	Strong protection
V	> 0.0280	< 40	Very strong protection

However, the protection levels might be invalid for other locations because the relationship between the V index and the minimum required mangrove band width was only set to a wave height of 3 m. Therefore, any lesser or great maximum wave height is not applicable for this protection level threshold. Besides, based on the obtained V index at every location, it was found that the southern region in the Vietnam coast was better protected than the northern region.

2.3.3.2 Mangrove Adequacy Assessment in Perak, Malaysia

Research has also attempted to evaluate mangrove adequacy in the west coast of Peninsular Malaysia in 2018 [9], which mainly focuses on the Perak coastline. The study identified 26,811 ha of mangroves sheltering along the coastline in the studied area, as presented in Figure 2.11. Large populations were found in the northern region of Perak, especially in Matang (referred to as point S2 in Figure 2.11), with *Rhizophora* as the dominant species. Meanwhile, only small patches of mangroves were observed growing in the south.

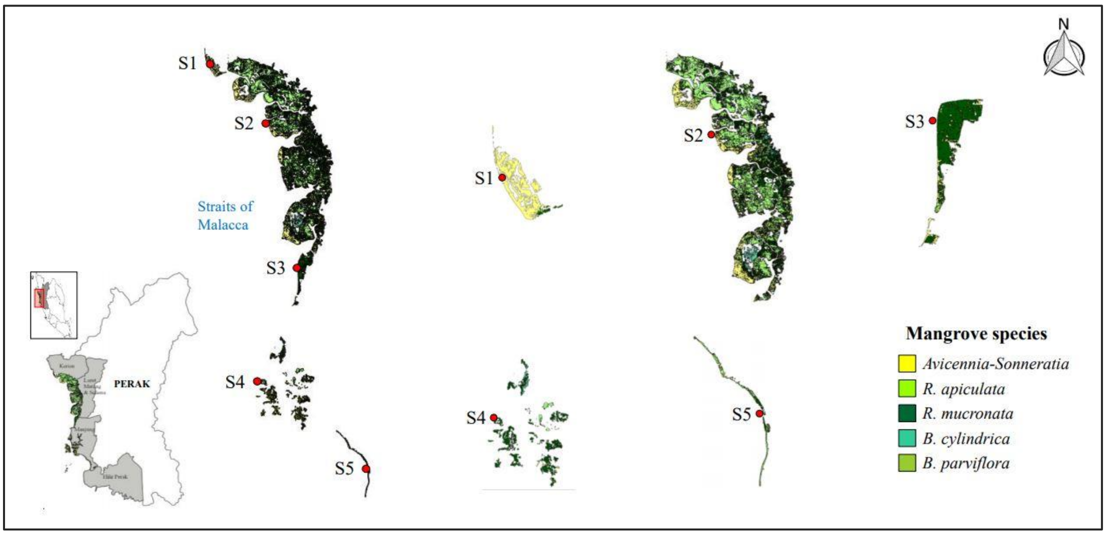


Figure 2.11: Mangrove distribution along the Perak coastline [9]

However, only the *Rhizophora* species were analyzed for the adequacy assessment since it has outstanding performance in wave dissipation compared to other species [61] with respect to the root properties, aside from to the vast population of Rhizophora in Perak coastline. Species, width, and age are the critical factors recognized in the assessment, but other affecting factors such as density were not addressed and taken into account. In terms of attenuation performance, Matang was reported to have the greatest reduction rate of 97% over its minimum width. However, Lekir (referred to as point S5 in Figure 2.9) that represents the south was expected to have the lowest reduction rate of 10%.

In this study, the transmitted wave height of above 0.3 m was classified to be at the danger level. The height of 0.3 m was set as the safe wave height [8], which explains that if the height was higher than 0.3 m after the wave travelled through the mangrove belt, then this indicates a danger alert. However, all sites were marked as safe over the normal wave height, except for Lumut and Lekir since both of the locations recorded a transmitted wave height of 0.37 and 0.45, respectively. More details on the transmitted wave heights and safety levels are tabulated in Table 2.5.

Table 2.5: Safety levels of mangrove forests [9]

Location		**Transmitted wave height, m**	**Safety level:**	
			Safe	**Danger**
Perak	Kuala Gula	0.23	/	
	Matang	0.01	/	
	Pantai Remis	0.15	/	
	Lumut	0.37		/
	Lekir	0.45		/

Subsequently, a significant level of insurance was required by establishing adequate width in the danger prone area. Hence, replantation was suggested in Perak, especially in Lumut and Lekir areas with a variety of widths depending on the age of mangroves to be planted, as shown in Table 2.6. The establishment of enough greenbelt, thus, assists in maintaining the buffering function of mangroves from the disastrous effects of storm surges, floods, and other natural hazards.

Table 2.6: Required *Rhizophora* widths for adequate protection according to the respective age [9]

Location	Required forest width, m			
	5 years	**10 years**	**15 years**	**20 years**
Lumut	65	20	13	9
Lekir	160	50	33	27

2.3.3.3 Mangrove Adequacy Assessment in Kedah, Malaysia

Another mangrove adequacy assessment was conducted in another part of west coast of Peninsular Malaysia, which is Kedah [10]. Their study was only covering the coastline of Kedah mainland. Field assessment was carried out to measure the detail geometry of the mangrove, followed by GIS process to develop the mangrove distribution map in Kedah. Mangrove coverage was largely identified in Merbok, meanwhile the highest mangrove density was recorded in Kuala Kedah. *Avicennia* appeared as the major species found. Bao's formula (see Equation 2.7) [8] was adopted for waves analysis. However, the limitation in this study is that they unable to obtain the real wave data and only provided with the expected range (limited to only 0 up to 60 cm) of wave height while analyzing the wave findings.

The paper argued on Bao's study for not grouping the similar mangrove of different age and density together. The researcher objects this argument since the delineation has been made by adopting the specific parameters on the density and geometry (including the tree height which represents the age) in their equations. Ahmad Herison formulation (see Equation 2.3) [80] was later incorporated for the wave dissipation analysis. Their findings shown that the highest wave attenuation of 1.14 m occurred in Kampung Sala. From their adequacy analysis, it was revealed that only Sungai Daun provides the strong protection towards the coastline while the rest studied areas were mostly having moderate to weak protection.

2.4 Remote Sensing

Remote sensing is described as the technology used to obtain information about objects or areas from a distance through space-borne sensors, usually from an aircraft or satellite [101, 102]. The satellite images captured using the technology are grouped into aerial photographs, medium-resolution data, high-resolution data, and hyper spectral data [103] depending on the spatial resolution. Remote sensing can provide information on a large scale [104, 6] and process both quantitative and qualitative measurements of mangroves through full utilization of the electromagnetic spectrum [4].

Furthermore, the remote sensing approach represents a cost-efficient method rather than in-situ field measurement [105, 106], especially when the observation is done on a large scale. Nowadays, free satellites images are increasingly available with a wide range of resolutions and time scales, which provides cost-effective and timely data acquisition even over the wide and inaccessible areas [107] that limit the mobility in the observational area due to unconsolidated and thick mud, inundation by high tides, and abundant stem and root systems [108].

The distinctive environmental factors affecting the growth of mangrove forests include the distance from the sea or coastline, frequency and duration of wave inundation, salinity, and soil composition. These important factors can, in some cases, become barriers in accessing and managing mangrove forests [101]. One of the best alternatives to overcome this shortcoming is by utilizing the advanced technology of remotely sensed image data, which provides a more accurate way of measuring and serves as an efficient tool for managing mangrove forests. On this basis, the spatial distribution of mangrove mapping would be effectively produced using the advanced technology of remotely sensed data and the Geographic Information System platform.

2.4.1 Aerial Photograph

An aerial photograph can produce, although small-scale, highly detailed coastal mapping [103, 109]. The images are normally obtained from an aircraft or Earthorbiting satellite where the high-resolution camera is mounted for image capturing [110]. While the mapping is restricted to only a narrow area, the identification output is very precise [2]. Nevertheless, the quality of images relies on the local atmospheric conditions [111]. This low-cost, or usually free images with vast availability, are classified based on the structures, textures, tone (contrast or colour) conditions, and other images for species identification [103, 112].

Mangrove mapping demonstrates the ability of aerial photographs in spatial analysis. Mangrove cover change detection in Sungei Buloh, Singapore revealed that the coverage of mangroves decreased due to the clearance for aquaculture, changes in the local hydrodynamic regime, and coastal erosion that probably resulted from the construction of Kranji Dam [113]. Moreover, mangroves of 15,000 ha in Moreton Bay encountered losses of more than 3,800 ha in the previous 25 years [114]. The re-establishment of mangroves was also detected over the same period, thereby recovering the losses, and leaving a net loss of only 200 ha.

Aside that, there was some mangrove mapping produced through the combination of aerial photograph with other satellite images. Sulong et al. [2] have integrated aerial photograph together with Landsat imagery and identified fourteen different types of mangrove forests in Kemaman, Terengganu, which are probably one of the most diverse mangrove forests in Malaysia. In delineating mangrove species, Heenkenda et al. [104] compared the accuracy using aerial photograph and WorldView-2 (a high-resolution image). They later concluded that WorldView-2 has higher accuracy than the aerial photograph with overall accuracy of 89%.

2.4.2 Medium-Resolution Satellite Image

Medium-resolution satellite imagery such as Landsat series, Sentinel-2, and Moderate Resolution Imaging Spectroradiometer (MODIS) is extensively selected over high resolution. Such preferences are due to the availability and free accessibility of the data imagery. Medium-resolution imagery is low cost, usually free, covers a large area, and has several multispectral bands and long-term satellite. However, the typical problems of using this are that it often involves coarse spatial resolution and has a different angle of data captures with a high frequency of cloud covers [115, 116, 117].

The Earth Resources Technology Satellites (ERTS), before being renamed Landsat 1, was launched in 1972. Subsequently, Landsat 2, Landsat 3, Landsat 4, Landsat 5, Landsat 6, Landsat 7, and Landsat 8 were introduced. Landsat 5 is the longest operating satellite after 28 years and 10 months of operation [118]. Meanwhile, MODIS has been broadly utilized in 2000, which is available in the National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey (USGS) platform. Due to the advantages of these medium-resolution images including the provision of multispectral data, the applications are extensive [103].

27,014 ha of mangrove forest was identified in Meghna Deltaic Islands, Bangladesh, with three species including *Sonneratia*, *Avicennia,* and *Excoecaria*. Landsat TM was applied to map the mangrove cover [119]. Meanwhile, in Puttalam Lagoon, Sri Lanka, Landsat MSS, Landsat TM, Landsat ETM+, and Landsat OLI were adopted in detecting the mangrove cover change [120]. A declination rate of 62% was observed between 1977 and 2015. Expansion of shrimp ponds that contributed to 1,371 ha of losses was the main cause of degradation.

A study by Omar et al. [4] discovered the decrease in mangroves coverage from 650,311 ha in 1990 to 629,038 ha in 2017. Each mangrove distribution constituted 60% in Sabah, 22% in Sarawak, and 18% in Peninsular Malaysia. The mangrove cover mapping and monitoring incorporated the imageries of Landsat-5 TM, Landsat-7 ETM+ and Landsat-8 OLI. Through Landsat series too, a reduction trend was recorded in Johor, Malaysia where 6,740 ha of mangrove area has been degraded from 1989 to 2014 [111]. 710 ha of mangroves were rectified through replantation, which resulted in a net loss of 6,030 ha.

2.4.3 High-Resolution Satellite Image

The launching of IKONOS, SPOT, QuickBird, WorldView-2 and RapidEye offer new opportunity to perform spatial analysis with higher resolution of satellite imagery. The spatial resolution data was enhanced up to 1.65 m in multispectral bands and 0.41 m in panchromatic bands which processes more detailed data [121]. Similar to aerial photographs, these high-resolution imageries can identify objects and properties precisely, defeating the shortcomings of aerial photographs as they are able to cover large-scale areas [122] in short intervals [123]. Albeit equipped with various advantages including minimum cloud cover, they are costly and have limited data availability [124]. Table 2.7 and Table 2.8 present several examples of previous studies on mangroves mapping by adopting the high-resolution satellite imageries on both worldwide and national scales, respectively.

Table 2.7: The use of high-resolution satellite imagery in mangrove research scopes worldwide

Scope of Study	**Location**	**Satellite Data**	**Findings**	**Literature**
Mangrove zonation mapping	Mai Po, **Hong Kong**	SPOT 1, SPOT 4, SPOT 5, GF-1	A sequence of mangrove species zonation was observed with *Kandelia obovata* 2, *Avicennia marina*, and *Kandelia obovata* 1 that grew accordingly from seawards to landwards.	[104]
Mangrove cover mapping	Texas Gulf Coast, **Mexico**	QuickBird	The supervised and unsupervised maps indicated a good accuracy assessment for black mangroves except the unsupervised classification of site 1 with a user's accuracy of 60.9%.	[107]
Mangrove density mapping	Andaman Islands, **India**	LISS IV	Dense mangroves covering 283.10 ha of the mangrove canopy area, 957.05 ha with moderate density, 501.34 ha with sparse, and 101.40 ha of degraded mangroves.	[125]
Mangrove species mapping	Caribbean Coast, **Panama**	IKONOS and QuickBird	Distinguished three mangrove species, including black, red, and white mangrove, with comparison on the satellite data performance.	[126]

Table 2.8: The use of high-resolution satellite imagery in mangrove research scopes in Malaysia

Scope of Study	**Location**	**Satellite Data**	**Findings**	**Literature**
Land-cover mapping	Kelantan, **Malaysia**	QuickBird	Ten classes were assigned, including *Avicennia alba*, *Sonneratia caseolaris* and *Nypa fruticans*, coconut plantations, terrestrial vegetation, agricultural fields, aquacultural ponds, settlement areas, exposed mud banks, sandbars, and water.	[74]
Land-cover mapping	Penang, **Malaysia**	THEOS	Land-use was divided into five classes consisting of forest and grassland, water, urban land, bare soil, and mangrove, with the mangrove cover mostly found in the western region.	[127]

2.5 Spatial Mangrove Analysis Using Geographic Information System (GIS)

Geographic Information System (GIS) is a reliable and advanced tool designed to create, store, edit, analyze, and digitize remotely sensed data as well as displaying geographically referenced information for object detection and phenomenon changes [128, 102]. The GIS and remote sensing satellite imagery have been largely employed to identify the spatial distribution of mangroves, produce mangrove cover mapping, and provide information on changes in the mangrove ecosystem over a range of temporal and spatial scales. Analysis of mangrove changes over a certain period allows researchers to analyze and monitor the historical changes of mangroves. Thus, GIS and remote sensing have been widely utilized since efficient, accurate, and repeated assessments can be produced through this approach [4].

Spatial analysis of mangroves, specifically the coverage mapping, adopts the processes of radiometric and geometric correction, classification [107], and validation of mapping accuracy through ground-truthing [129, 71, 130, 120], before subsequently converting the rasterize data to the vector form [7]. The classification comprises supervised and unsupervised classification. Supervised classification requires the user to assign training samples for the recognition of common pixel images, while unsupervised classification, on the other hand, lets the software automatically run the classification process based on the defined number of classes.

Vegetation indices such as Normalized Different Vegetation Index (NDVI), Normalized Difference Infrared Index (NDII), Different Vegetation Index (DVI), Ratio Vegetation Index (RVI), Wetland Forest Index (WFI), Infrared Percentage Vegetation Index (IPVI), Forest Discrimination Index (FDI), and Green Atmospherically Resistant Index (GARI) can also be derived from the images for better classification quality [131, 132, 125, 21]. Integrating these techniques during the classification process, thus, increases the accuracy in distinguishing the different species of mangroves [102].

2.6 Summary

Mangroves demonstrate a vital function towards the coastal ecosystem in terms of reducing severe wave actions, controlling erosion, promoting sedimentation, and stabilizing the shoreline. Mangroves serve as a natural shield and act as an obstruction towards incoming waves, resulting in the attenuation of wave heights over the distance into mangrove forests. This coastal vegetation further absorbs the wave energy, decays the wave height, and lessens the wave impact. Nevertheless, the coverage of mangroves in Malaysia is of great concern where degradation occurs at an alarming rate. The west coast of Peninsular Malaysia was affected during the 2004 Indian Ocean Tsunami, indicating the significance of adequate protection to buffer the coastline and its communities from future disasters.

The current distribution of mangroves inhabiting the coastline demonstrates the current protection along the coast and, therefore, needs to be assessed by adopting remote sensing and GIS technology. Considering the wide accessibility of Landsat imagery and its accuracy in mangrove mapping, hence researcher attempted to utilize this medium-resolution satellite data. Aside from that, observing wave behavior in particular locations is also required. Bao's formula as derived from the literature will be opted for analyzing transmitted wave height for its comprehensive formula which encompassing all affecting attenuation factor.

Thus, the two important scopes as a pre-requisite for studying mangrove dissipation performance can be grouped into mangrove parameters (e.g., structures, widths, densities) and wave parameters (e.g., incident wave heights, transmitted wave heights). Prior to the determination of mangrove sufficiency, the current coverage of mangroves and the required coverage should be compared. Bao's formula again will be incorporated in order to determine the required minimum coverage and assess the significant level of insurance from high waves and coastal disasters. At the end of the analysis, replantation will be suggested to the vulnerable and high-risk areas so that the buffering capacity of mangroves can be utilized to the maximum level.

CHAPTER 3

METHODOLOGY

3.1 Overview

Chapter 3 discusses the physical settings of this study as well as the methods and approaches adopted in the determination of wave dissipation by mangroves along the Kedah coastline, where the findings obtained are aligned with the research objectives. In addressing the currently inadequate mangrove distribution along the coastline, a field study and GIS analysis were undertaken in eight study areas. Next, a wave analysis was carried out, which comprises wave heights and wave dissipation analysis. The relationship between mangrove structures and wave actions were also analyzed to further assess mangrove adequacy through an assessment using Bao's formula. Finally, the research flowchart is presented to briefly depict the work sequence.

3.2 Description of the Study

The state of Kedah (Figure 3.1), which is located on the west coast of Peninsular Malaysia, was chosen as the project site for this study. Kedah is bordered by Penang on the south and Perlis on the north. It is subjected to a semi-diurnal tidal regime with two high and low tides occurring each day. Tidal levels at few coordinates in Kedah that were obtained from Admiralty Chart by the National Hydrographic Centre, Malaysia [133] are recorded in Table 3.1.

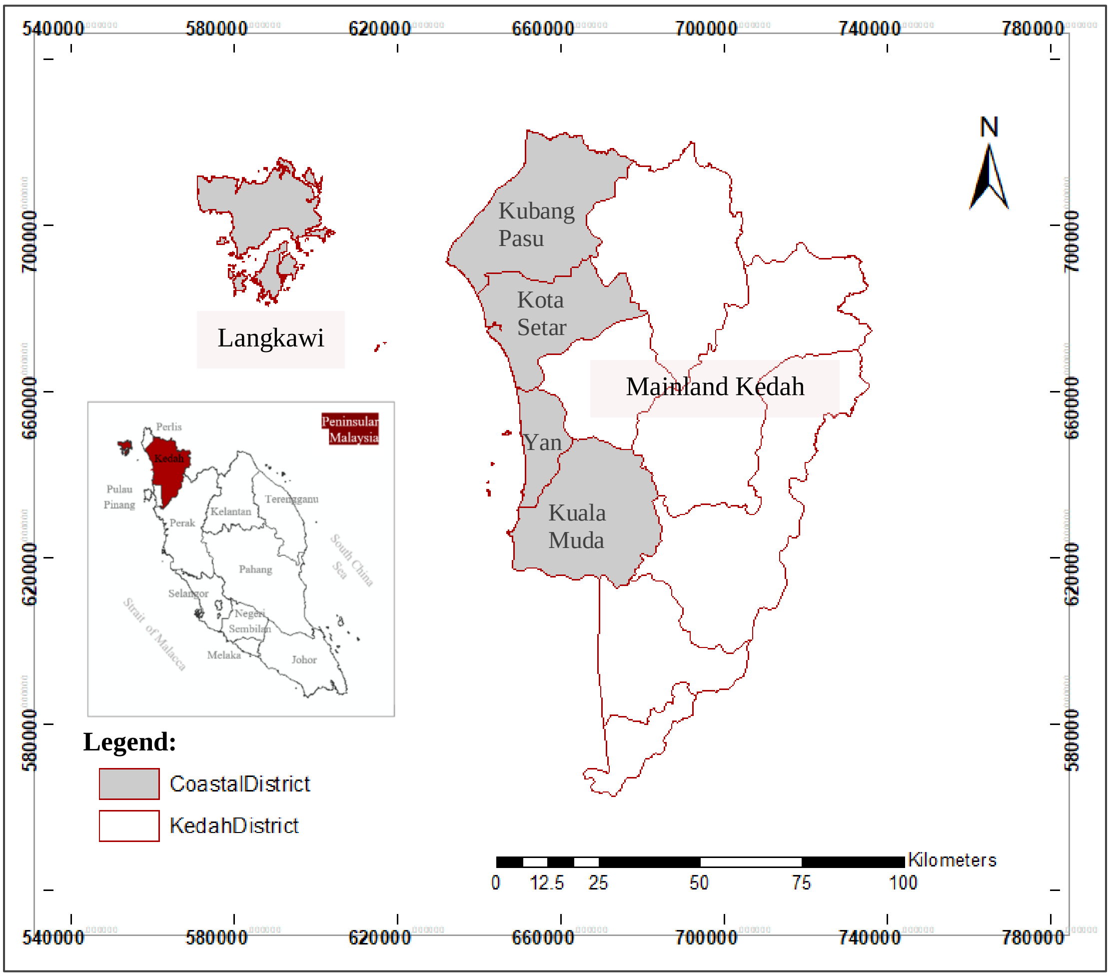


Figure 3.1: Study areas

Table 3.1: Tidal levels at several locations in Kedah

Location	Latitude (N)	Longitude (E)	Height above Datum (m)			
			MHWS	MHWN	MLWN	MLWS
Tanjung Dawai	5° 40'	100° 17'	2.7	1.9	1.3	0.5
Pulau Bidan	5° 45'	100° 17'	2.6	1.8	1.3	0.5
Kuah	6° 18'	100° 17'	2.7	1.9	1.3	0.5
Teluk Datai	6° 26'	100° 17'	2.8	2.0	1.3	0.5
Teluk Ewa	6° 26'	100° 17'	3.1	2.2	1.5	0.6

Kedah records an average annual temperature and humidity of 29ºC and 80%, respectively. This study covers the coastline of both mainland Kedah and Langkawi Island. Mainland Kedah is located between 6° 15' 6.5232" N to 5° 34' 41.142" N and 100° 11' 41.9424" E to 100° 20' 25.0656" E, while Langkawi is situated between 6° 28' 39.846" N, 99° 49' 30.6732" E to the northern edge and 6° 28' 25.7772" N, 99° 49' 44.0832" E to the southern edge. The coastline stretches along the five districts in Kedah, namely Langkawi, Kubang Pasu, Kota Setar, Yan, and Kuala Muda.

Eight locations were selected for field assessment, namely Kuala Muda, Merbok, Sungai Daun, Kangkong, Kuala Kedah, Jerlun, Sungai Melaka, and Kuala Teriang. These are among the mangrove-populated areas along the coastline in which some were experiencing devastating damages during the 2004 IOT. Figure 3.2 illustrates the locations of the study areas, while the coordinates are listed in Table 3.2.

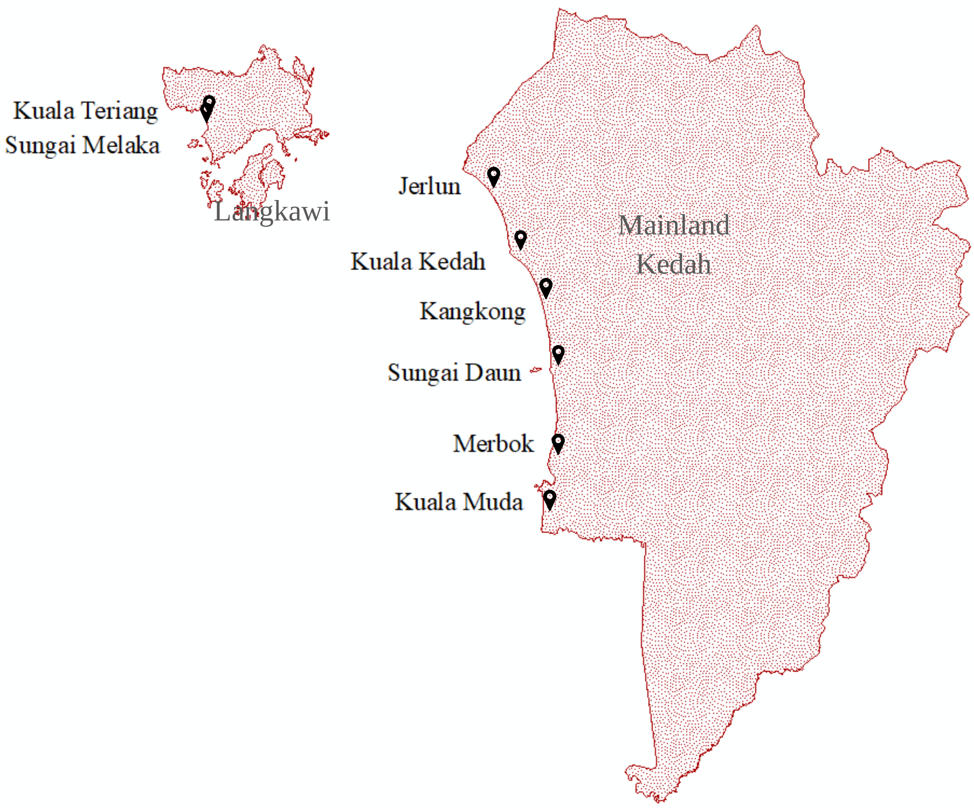


Figure 3.2: Locations of study areas

Table 3.2: Coordinates of locations

District	Location	Coordinate	
		Latitude	Longitude
Langkawi	Kuala Teriang	6° 21' 39.32"	99° 42' 45.41"
	Sungai Melaka	6° 21' 16.88"	99° 43' 0.61"
Kubang Pasu	Jerlun	6° 13' 13.69"	100° 14' 1.93"
Kota Setar	Kangkong	6° 0' 5.09"	100° 20' 29.66"
	Kuala Kedah	6° 4' 51.29"	100° 17' 56.23’’
Yan	Sungai Daun	5° 52' 48.00"	100° 21' 19.71"
Kuala Muda	Kota Kuala Muda	5° 35' 19.19"	100° 20' 20.28"
	Merbok	5° 41' 24.75"	100° 21' 21.38"

3.3 Data Collection

In achieving the research objectives, mangrove and wave data were required for further analysis. Mangrove data were collected through field assessment, while wave data were obtained from the Department of Irrigation and Drainage (DID), Malaysia.

3.3.1 Field Assessment

Field assessment was conducted from 15th to 18th April 2019, covering eight study sites as previously mentioned in Table 3.1. The purpose of this visit is to gain an overall overview regarding the sites apart from obtaining on-site mangrove measurement. Besides, this assessment also serves as part of the initial ground-truthing process before performing the Geographical Information System (GIS) mapping. Figure 3.3

shows the activities conducted during the assessment, which comprises the measurement of mangrove densities and structures.

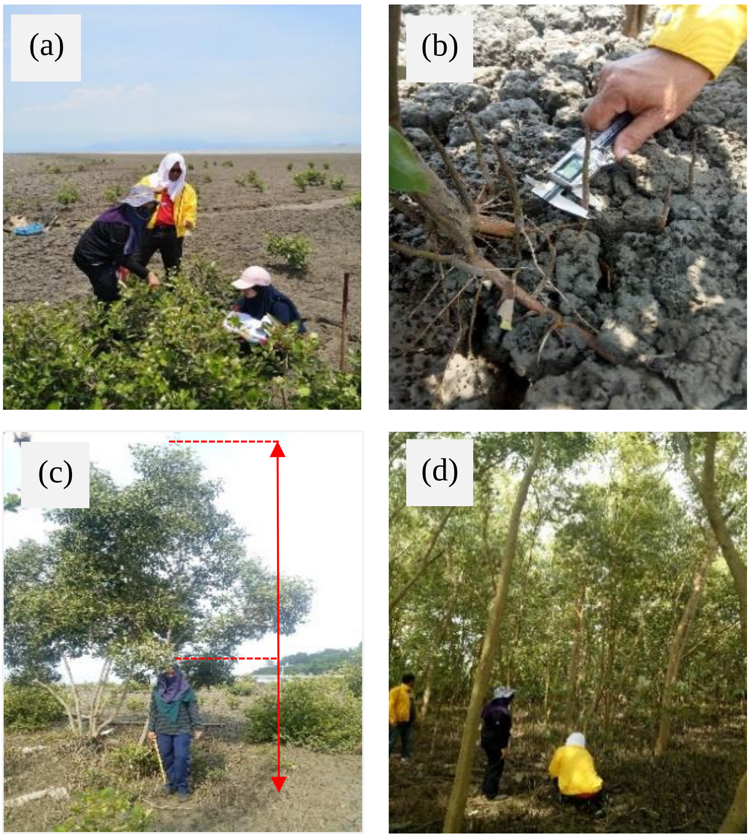


Figure 3.3: (a) Mangrove identification and measurement (b) Measuring root diameter using caliper (c) Tree height measurement (d) Matured mangrove in Merbok

Mangrove structures include the height of trees, height of canopies, height and diameter of trunks, diameter at breast height (DBH), and root geometries such as the band width, diameter, and height of roots. The diameter component was measured using a measuring tape and caliper according to the suitability fit of the tools. Meanwhile, the height component was measured using a measuring tape. A scaling method was also applied in the measurement in such a case that the measuring tape did not occupy the tree height. Human height was taken as the reference object and compared with the tree height to approximately estimate the actual tree height (refer to Figure 3.3 (c)).

The coordinate of each tree was recorded using a hand-held Global Positioning System (GPS). Three (3) plots, each with an area of 100 m^2 (10 m x 10 m) were set up at each study area. These plots were in ascending arrangement landwards. The number of trees in each plot was calculated to determine the density of mangroves and the species for the assessed mangroves were also recorded. Density for each site was calculated by applying the following formula:

$$\text{Density} = \frac{\text{Total number of tree in three plots}}{\text{Area of plots}}$$

The measurement for *Avicennia* spp., *Sonneratia* spp., and *Brugeria* spp. was based on the guideline in Figure 3.4, while the measurement for *Rhizophora* spp. is depicted in Figure 3.5.

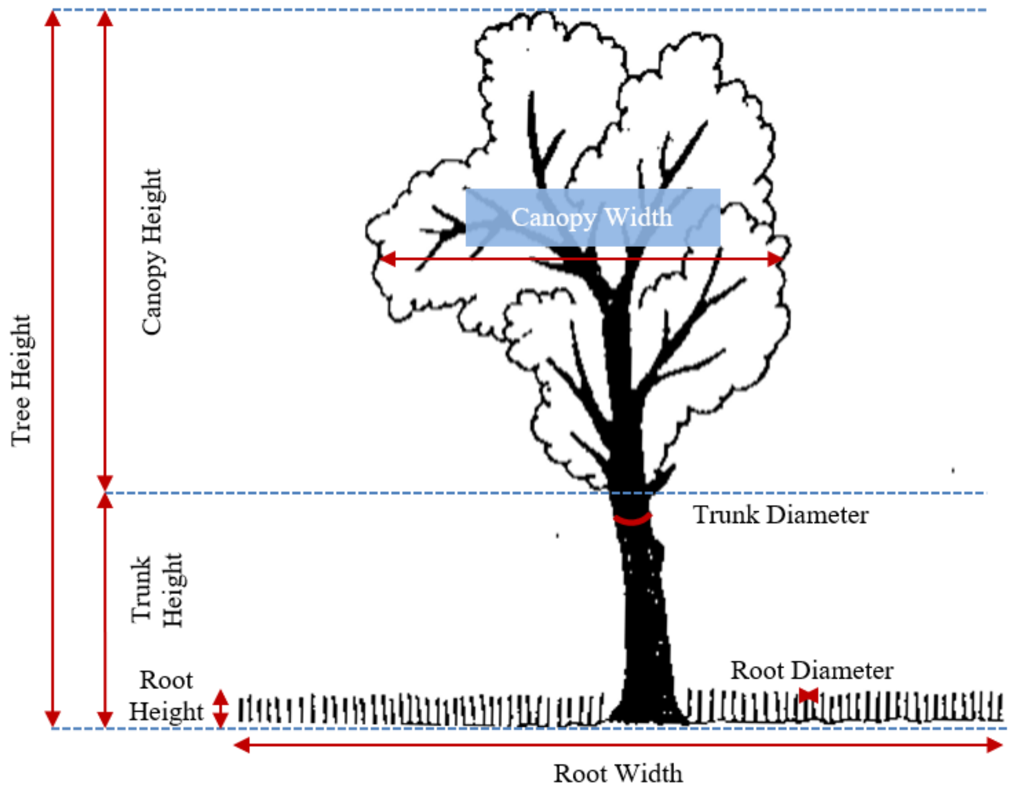


Figure 3.4: Detailed structures of Avicennia spp., Sonneratia spp., and Brugeira spp.

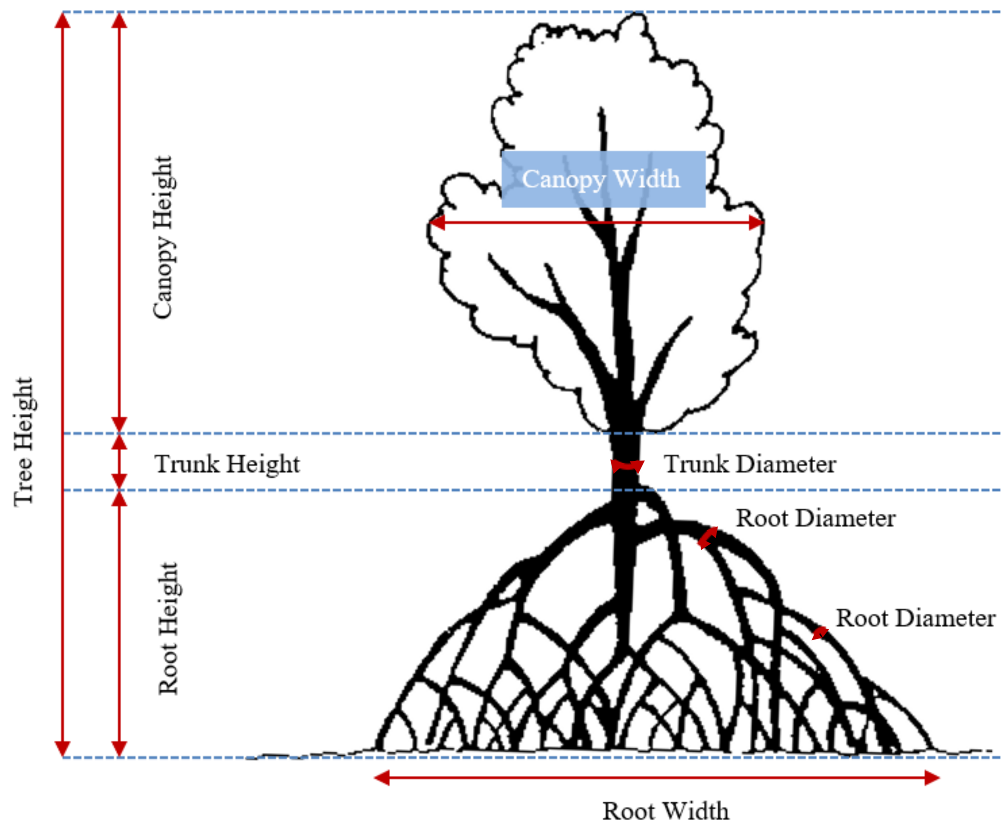


Figure 3.5: Detailed structures of Rhizophora spp.

No tides were flooding the mangrove areas during the data collection, thus enabling the mangrove measurement to be conducted. In the case of high tides, the accessibility to the sites might be restricted by the flood and high muddy substrates [134]. Hence, it is recommended to conduct mangrove sampling during low tides during the neap tide periods. In contrast to neap tides, the low tides will be lower and the high tides will be higher than usual during spring tides.

3.3.2 Wave Data

Wave conditions such as significant wave height, peak wave period, and wave directions for each study site were provided by the Department of Irrigation and Drainage (DID) Malaysia [135]. The significant wave height of 0.99 m was obtained from the average of the highest one-third of the wave height over 40 years. Figure 3.6 indicates the wave rose diagram in Kedah.

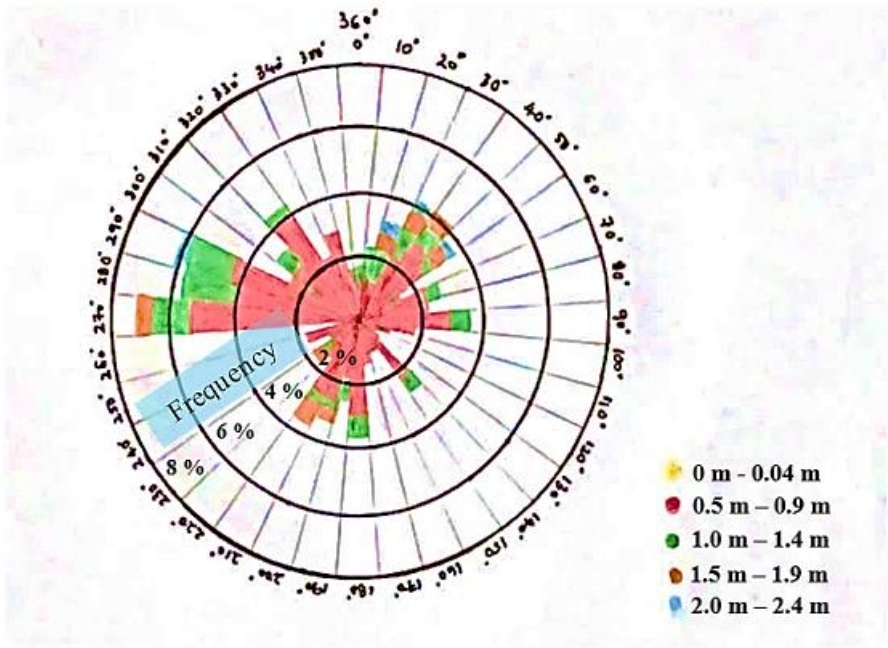


Figure 3.6: Wave rose diagram in Kedah

This data was compared with the significant wave height generated from the satellite altimeter [136] for validation and reliability testing. The dataset from the Northeast monsoon was chosen since it is rougher than the other monsoon periods. The mapped wave height depicts that Kedah waters (red box region in Figure 3.7) have a significant wave height ranging from 0.8 m to 1.1 m along the mainland and 0.6 m in the coastline of Langkawi.

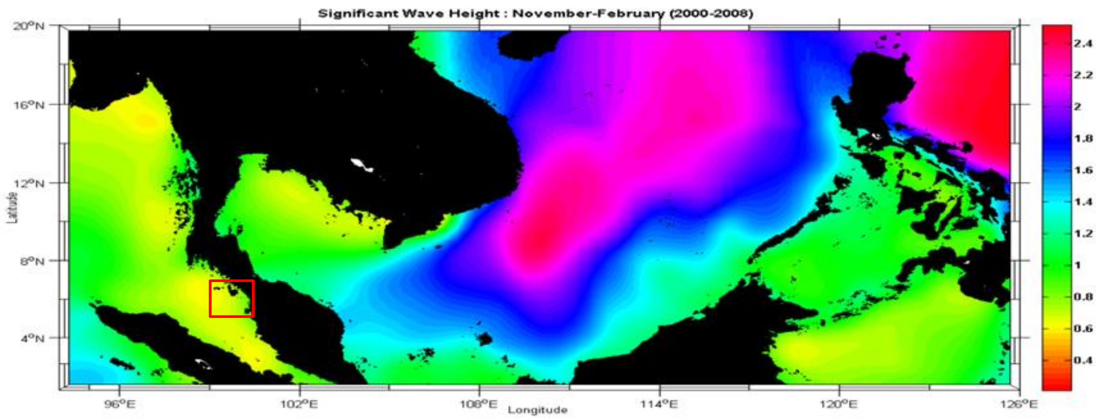


Figure 3.7: Significant wave height during Northeast monsoons in Malaysian seas in 2000 – 2008 [136]

3.4 Data Processing

Mangrove data accumulated from the field assessment were further used as a reference for remote data processing. Apart from that, raw wave data were also interpreted and processed using wave transformation analysis.

3.4.1 Remote Sensing Data Processing

Remote Sensing and Geographical Information System (GIS) tools were employed to uniquely map the current coverage of mangroves in the respective coastal area. Image processing and mapping were performed in the GIS platform, specifically ArcGIS version 10.3. The tools were used to calculate the total area and canopy closure of mangrove coverage. Mangrove band widths were also determined from the map produced. This eventually helps derive the resilient level of the existing mangrove buffer to protect against the prevailing wave attack. Figure 3.8 summarizes the flow of these processes.

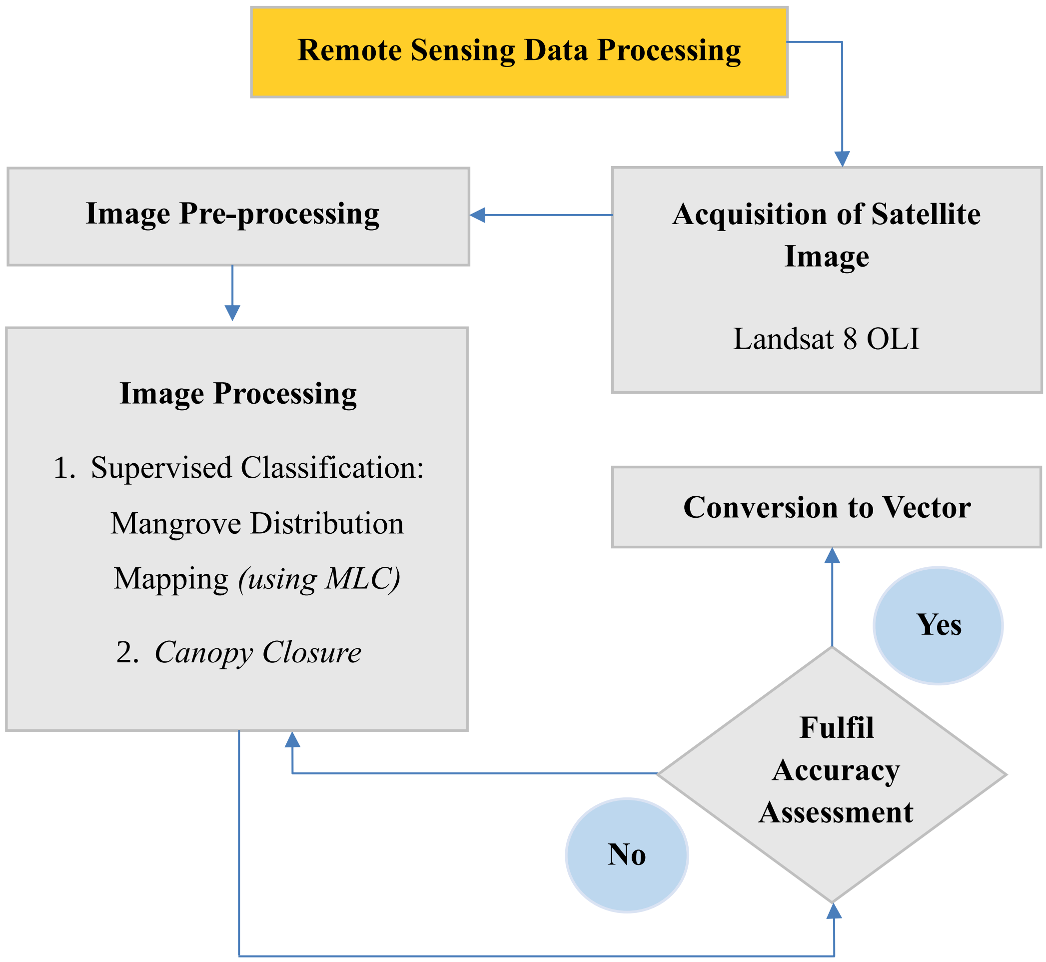


Figure 3.8: Flow of remote sensing data processing

3.4.1.1 Satellite Data Acquisition

Several sets of Landsat-8 Operational Land Imager (OLI) [4, 105] satellite images with 30 m resolution were utilized to derive the mangrove coverage in the study areas. These images are available on the U.S. Geological Survey (USGS) website [137]. In the production of Kedah mapping, two scenes with path/row ID of 128/056 and 129/056 (Figure 3.9) were adopted. The scenes, respectively dated 24th January 2019 and 4th March 2019, were selected due to the minimal cloud cover over the Kedah boundary that was below 10%. Besides, satellite images solely within January to June 2019 were opted for processing to provide the current mangrove distribution in Kedah.

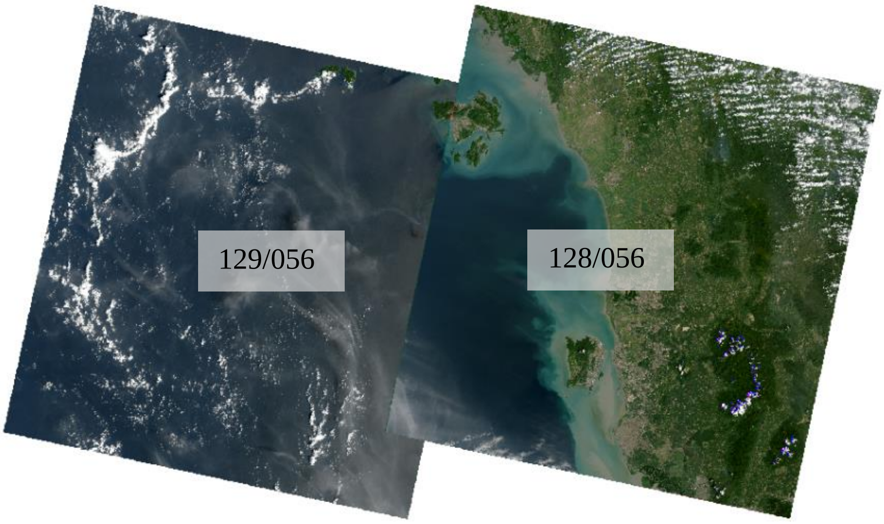


Figure 3.9: Satellite images of path/row ID 129/056 and 128/056, respectively

3.4.1.2 Pre-processing Image

Noises from the satellite images should be eliminated by performing atmospheric correction [9]. Cloud cover might be present on the images acquired by the satellites; thus, a method to remove cloud cover by Omar et al. [4] was done by merging several images of scenes captured over the same year. The cloud patching process enhances the images and removes the cloud covers. As illustrated in Figure 3.10, the red shaded boundary marks Kedah territory and the white figures are the clouds captured on the images.

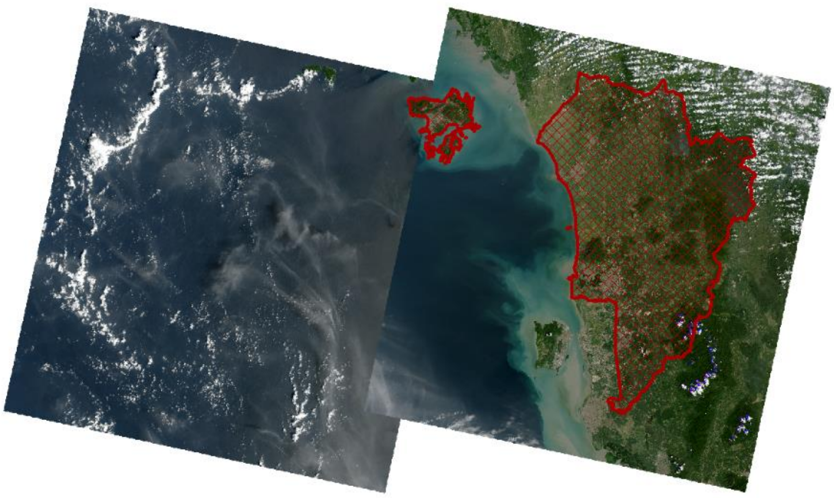
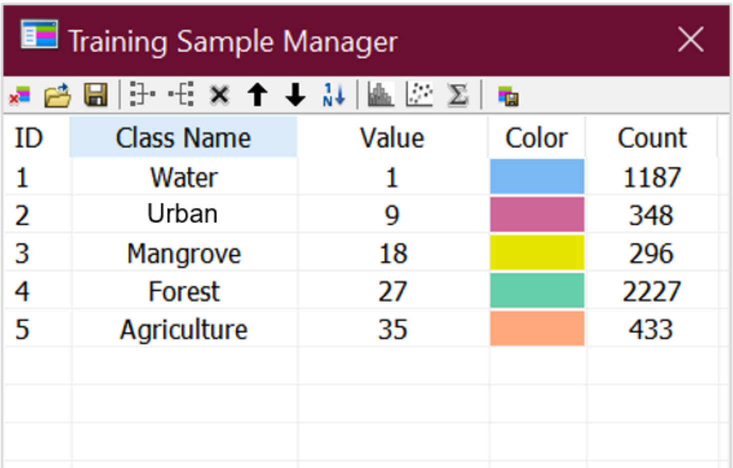


Figure 3.10: Cloud covers on satellite images

Since the clouds in the selected scenes were not covering or blocking the study areas especially along the coastline, no cloud removal was implemented. Next, the individual scenes were mosaicked, and extraction was performed. A new shapefile of the Kedah boundary was created using IGIS Map Tool. Kedah as the region of interest was clipped out from the raster cells. The colour composite of bands Red, Green, and Blue were respectively set as 5, 4, 3 (RGB = 5-4-3).

3.4.1.3 Image Classification

The satellite images were classified using the supervised classification approach. The traditional classification method of Maximum Likelihood Classification (MLC) [7, 9] was adopted. MLC is the most used technique [138] and has been regarded as the most effective method to delineate the category [102]. Vegetation indices such as Normalized Different Vegetation Index (NDVI) improves the quality of classification [4] and was applied to distinguish the vegetation cover of mangrove canopies.


Training Sample Manager

ID	Class Name	Value	Color	Count
1	Water	1		1187
2	Urban	9		348
3	Mangrove	18		296
4	Forest	27		2227
5	Agriculture	35		433

Figure 3.11: Training samples for classification

Images were classified into five different classes comprising water, urban, mangrove, forest, and agricultural. Five (5) to ten (10) training samples were assigned to each class (Figure 3.11). Rather than allowing the software to delineate and classify the land-cover on its own as in the unsupervised classification approach, supervised classification, on the other hand, requires few training samples to be developed. This training set also helps the software recognize the other land-covers based on the same pattern of the assigned pixels.

Mangroves usually appear darker on the satellite images due to the higher chlorophyll content on the mangrove leaves than other trees [119]. Healthy vegetation of growing lush green covers show a higher NDVI value compared to environmentally stressed matured trees due to poor tidal inundation or excessive sand deposition [138].

3.4.1.4 Canopy Closure

Canopy closure resembles the amount of light that can penetrate the forest floor over the segmented sky as viewed from a single point. Advancement in remote sensing and GIS technology enables the calculation of canopy closure, thus substituting the need for in situ measurement. Any mangrove pixel that is taller than 0.8 m [139] was considered as a tree in the software. This symbolizes the height of mid-age and matured trees that can withstand the incoming wave [97].

3.4.1.5 Ground-truth Verification

Mangrove data obtained from the initial field assessment serves as important ground verification information and provided an initial overview of the sites before developing the geospatial map. As a post-processing procedure of GIS mapping, ground-truthing was conducted to assess and verify the accuracy of the mangrove mapping produced with the real ground data in the same coordinates [2].

Positional accuracy, as defined by [129], is the accuracy of the location in the satellite imagery with the reference location on the ground. Overall, 43 points from all study sites were selected for verification during this process (Figure 3.12). The specific coordinates of these locations are listed in Appendix B.

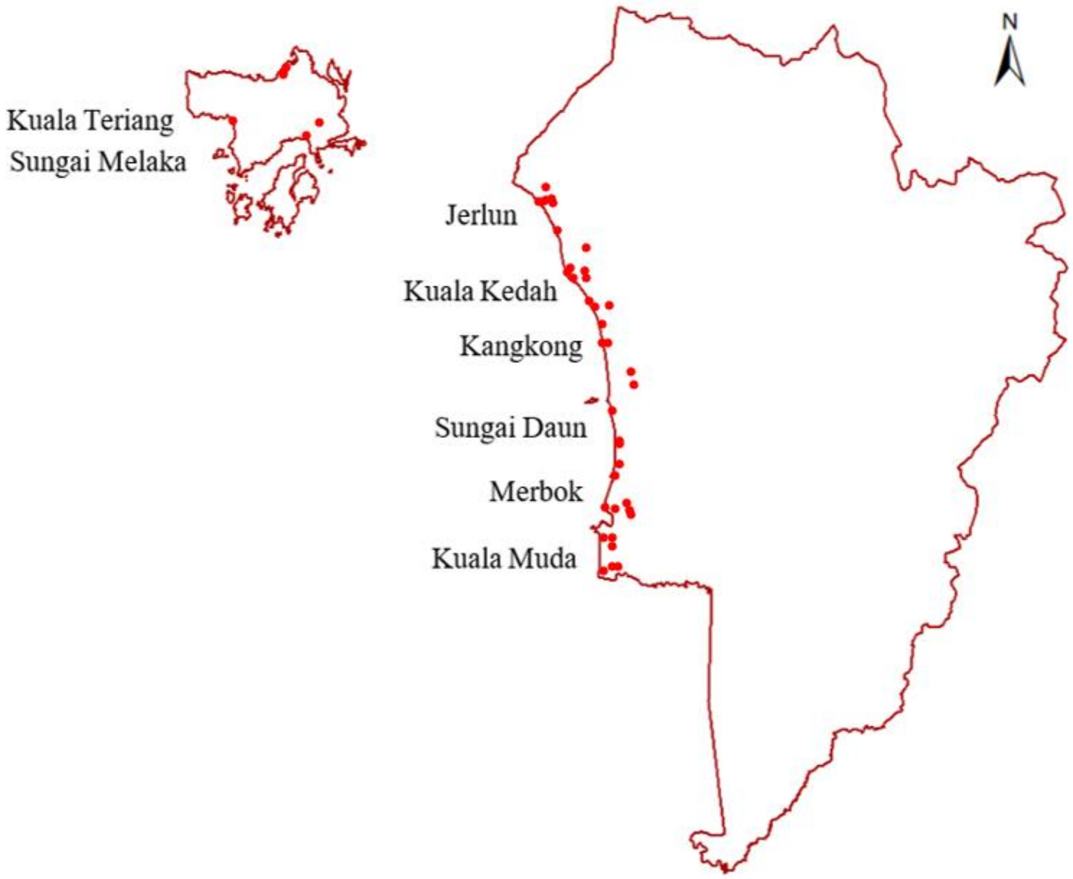


Figure 3.12: Landmark for ground-truthing process

Figure 3.13 demonstrates some site images from the ground-truthing process. Validation samples were taken randomly for each of the land-cover classes from 24th to 26th September 2019. The coordinates were recorded during the initial field and ground-truth assessment using the hand-held Global Positioning System (GPS). The locations were taken as reference points to validate the real ground and remote sensing data.

Figure 3.13: Verification of (a) water, (b) urban, (c) mangrove, and (d) agriculture classes as classified in the GIS map

3.4.1.6 Accuracy Assessment

Due to some constraints and limitations in the geospatial processing, some errors might occur in the image classification. Thus, a standard error matrix was adopted to enhance image accuracy. The matrix, which is also known as the confusion matrix, signifies the classification model’s performance of a dataset. The rows of the matrix consist of data from the output map, while the columns of the matrix correspond to the ground-truth data [119]. The diagonal shows that the predicted (from the map) and actual (ground-truth) data are matching and correctly classified.

In the confusion matrix, the percentage classification accuracy was derived including user’s accuracy, producer’s accuracy, and overall accuracy. User’s accuracy indicates the probability of the classified data on the map that really presents the ground. Producer’s accuracy, on the other hand, is defined as the probability of the ground truth that is correctly classified on the map. Meanwhile, overall accuracy is the proportion of the ground-truth data that are mapped accurately. Table 3.3 illustrates a sample of the confusion matrix with a total of 130 datasets.

Table 3.3: Sample of confusion matrix

	Ground-truth (Actual)				
Classified (Predicted)	Water	Urban	Mangrove	**Total**	**User's Accuracy, %**
Water	**30**	4	2	36	83.3
Urban	8	**22**	3	33	66.7
Mangrove	6	7	**48**	61	78.7
Total	44	33	53	**N = 130**	
Producer's Accuracy, %	68.2	66.7	90.6		

The sample calculations for each classification accuracy of mangrove class are as follows:

Users' accuracy

= [Total of correctly identified data (bolded value in diagonal cell) of the class / total classified data of the class] * 100

= (30 / 36) * 100

= 83.3%

Producers' accuracy

= [Total of correctly identified data (bolded value in diagonal cell) of the class / total ground-truth data of the class] * 100

= (30 / 44) * 100

= 68.2%

Overall accuracy

= [Total of correctly identified data (bolded value in diagonal cell) / total number of datasets] * 100

= (100 / 130) * 100

= 76.9 %

3.4.1.7 Conversion to Vector Output

A raster image produced from the final classification land-cover results was then exported into vector format in shapefile form [140]. Conversion to vector form allows for further refinement and editing. Furthermore, analysis of the classification report yielded the input of percentage and area covered by each class as well as the percentage of canopy closure at each study site.

3.4.2 Wave Height Analysis

The approaching wave that governs the dissipation rate of mangroves was studied. The height of incident waves in front of the mangrove trees as well as the height of transmitted wave behind the mangrove trees was analyzed. The difference in the heights of both waves demonstrates the attenuation performance of mangroves.

Incident waves refer to the waves that travel towards the coast just before they hit the mangrove forest. All waves were in transitional condition; wave transformation analysis was performed on the significant wave height to ensure that all wave processes before and upon approaching the coastal area are taken into consideration in computing the incident wave height, H_i. Wave will transform as it approaches deep water and propagates into progressively shallower water depth. In this study, three coastal processes were analyzed including wave breaking, shoaling, and refraction.

Transmitted waves refer to the attenuated waves that have travelled through certain widths into the mangrove forest. Usually, the height, H_t is recorded lower than the incident waves due to the bottom friction and drag force from mangroves. The current study adopted Bao’s formula [8] in the calculation of transmitted wave heights.

3.4.2.1 Incident Waves: Wave Shoaling

As the waves travel into shallower bathymetry, they experience a shoaling effect by which when the wave steepness increases, the wavelength decreases but the wave period is maintained. Bed friction and turbulence at the bottom causes the waves to be slowed down and shortened. The shoaling coefficient, K_s was obtained from Shore Protection Manual (SPM) [141], while the height of wave shoaling was calculated as follows:

$$K_s = \frac{H}{H_0} = \sqrt{\frac{C_0}{2C_g}} \qquad \text{Equation 3.1}$$

Where H is the shoaling wave height (m), H_0 is the significant wave height (m), C_0 is the deep-water celerity (m/s), and C_g is the wave group celerity (m/s).

Sample of calculation:

Location	= Jerlun
Significant wave height, H_o	= 0.99 m
Wave period, T	= 5.46 s
Depth, d	= 1.90 m

$$\frac{d}{L_o} = \frac{1.90}{46.5}$$

$$= 0.0408$$

Refer to the Shore Protection Manual (SPM) table to find $\frac{d}{L}$:

$$\frac{d}{L} = 0.0842$$

$$L = 22.57$$

Refer to Shore Protection Manual (SPM) table and applying Equation 3.1:

$$K_s \quad = \frac{H}{H_o} = 1.06$$

$H \quad = \ 1.05\ m$ (Shoaling wave height)

3.4.2.2 Incident Waves: Wave Refraction

When the wave moves over different bed contour, the wave crest bends and aligns with the bottom contour of different depth. The process is called wave refraction. The equation for refracted wave height is expressed as follows:

$$\frac{H}{H_o} \quad = K_s K_r \qquad \text{Equation 3.2}$$

Where H is the refracted wave height (m), H_o is the significant wave height (m), K_s is the shoaling coefficient, and K_r is the refraction coefficient. The K_r value from the SPM table was used.

Sample of calculation:

Location = Jerlun

Significant wave height, H_o = 0.99 m

By applying Equation 3.2:

$$\frac{H}{0.99} \quad = (1.06)(0.8747)$$

$H \qquad = 0.92\ m$ (Refracted wave height)

3.4.2.3 Incident Waves: Wave Diffraction

Diffraction is another process that occurs when the wave passes an obstruction in the form of a breakwater, opening, headland, and small island. This process commonly takes place in the near-shore zone where the wave propagation is interrupted, and the wave crest will eventually spread at the lee side of the obstacle. However, in this study, Pulau Bunting that is located approximately 2 km from Yan's coastline (refer to Figure 3.14) was ignored for its diffraction effect due to the insignificant size of the island and distance from the coastline. Therefore, no diffraction analysis was performed.

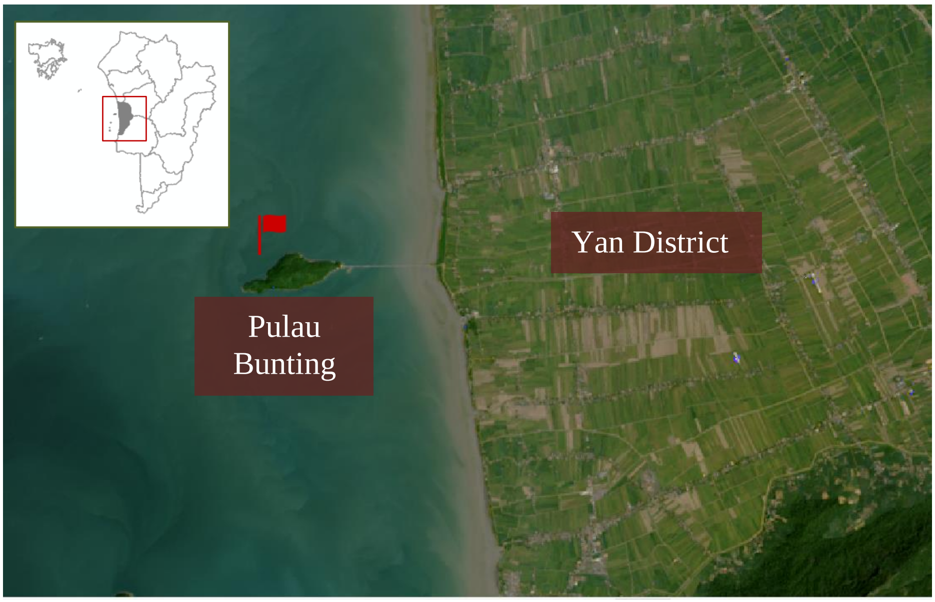


Figure 3.14: Pulau Bunting's location from Yan District

3.4.2.4 Transmitted Waves

Bao conducted a study to predict the wave height attenuated across the distance into mangrove trees with more than 80% correlation with the wave data measured in Cat Ba, Hoang Tan, Tien Lang, and Can Gio. The numerical Equation 3.3 is a combination of two coefficients, α and b, representing the relationship between the initial wave height reduction and mangrove forest structures.

$$W_h = (0.9899 \times I_{wh} + 0.3526) \times e^{(0.048 - 0.0016 \times H - 0.00178 \times \ln(N) - 0.0077 \times \ln(CC) \times B_w)}$$

Equation 3.3

Where W_h is the wave height behind the mangrove (cm), I_{wh} is the incident wave height (cm), H is the average mangrove height (m), N is the tree density (tree ha^{-1}), CC is the canopy closure (%), and B_w is the mangrove band width (m).

Sample of calculation:

Location	= Jerlun
Incident wave height, I_{wh}	= 1.05 m or 105 cm
Average mangrove height, H	= 3.7 m
Tree density, N	= 8,600 tree ha^{-1}
Canopy closure, CC	= 75 %
Mangrove band width, B_w	= 55.5 m

$$W_h = (0.9899 \times 105 + 0.3526) \times e^{(0.048-0.0016\times 3.7-0.00178\times ln(8,600)-0.0077\times ln(75)\times 55.5)}$$

= 70 cm or 0.70 m

3.4.3 Wave Dissipation Analysis

The wave dissipation rate is defined as the difference in the heights of incident waves and transmitted waves as the waves flow through mangroves. A reduction rate coefficient developed by [79] was used to demonstrate the dissipation rate of waves:

$$R\ (\%) = \frac{H_i - H_t}{H_i} \times 100 \qquad \text{Equation 3.4}$$

Where R is the coefficient of wave reduction (%), H_i is the incident wave height (m), and H_t is the transmitted wave height (m). Thus, based on this equation, the dissipation performance of mangroves can be studied.

Sample of calculation:

Location = Jerlun

Incident wave height, H_i = 1.05 m

Transmitted wave height, H_t = 0.70 m

$$R = \frac{1.05 - 0.70}{1.05} \times 100$$
$$= 33.8\ \%$$

3.4.4 Mangrove Adequacy Assessment

Assessment on the adequacy of mangroves in serving as coastal buffer correlates with the relation of several parameters as expressed in Equation 3.5 by [8]:

$$B_w = \frac{\ln(W_h) - \ln(a)}{b} \qquad \text{Equation 3.5}$$

Where B_w is the mangrove band width (m), W_h is the safe wave height behind the mangrove forest (cm), α is a function of initial wave height (Equation 3.6), and b is a function of the mangrove structure (Equation 3.7).

Safe wave height is obtained from the average of normally transmitted wave height. Meanwhile, the maximum wave height data over several years were accumulated to determine the average initial wave height. Equation 3.6 and Equation 3.7 below illustrate the functions of initial wave height and mangrove structure, respectively.

$$a = 0.9899 \times I_{wh} + 0.3526 \qquad \text{Equation 3.6}$$

where I_{wh} is the initial sea wave height (cm).

$$b = 0.048 - 0.0016 \times H - 0.00178 \times \ln(N) - 0.0077 \times \ln(CC) \qquad \text{Equation 3.7}$$

Where H is the average mangrove height (m), N is the tree density (tree ha^{-1}), and CC is the canopy closure (%).

Equation 3.5 reveals the minimum mangrove forest band width required for the respective mangrove geometries and wave conditions. Thus, the current actual mangrove band width along the Kedah coastline was compared to this required minimum band width, which eventually indicates whether or not the current mangrove coverage complemented the minimum required band width. Band width lower than the minimal value shows a requirement for future replantation in the area.

Sample of calculation:

Location	= Jerlun
Safe wave height behind mangrove forest, W_h	= 0.3
Function of initial wave height, α	= 104.23
Function of mangrove structure, b	= - 0.00729

$$B_w = \frac{\ln(0.3) - \ln(104.23)}{-0.00729}$$

$$= 802.5 \text{ m}$$

3.5 Process Flow

The chronology of the research process is listed in Figure 3.15 below.

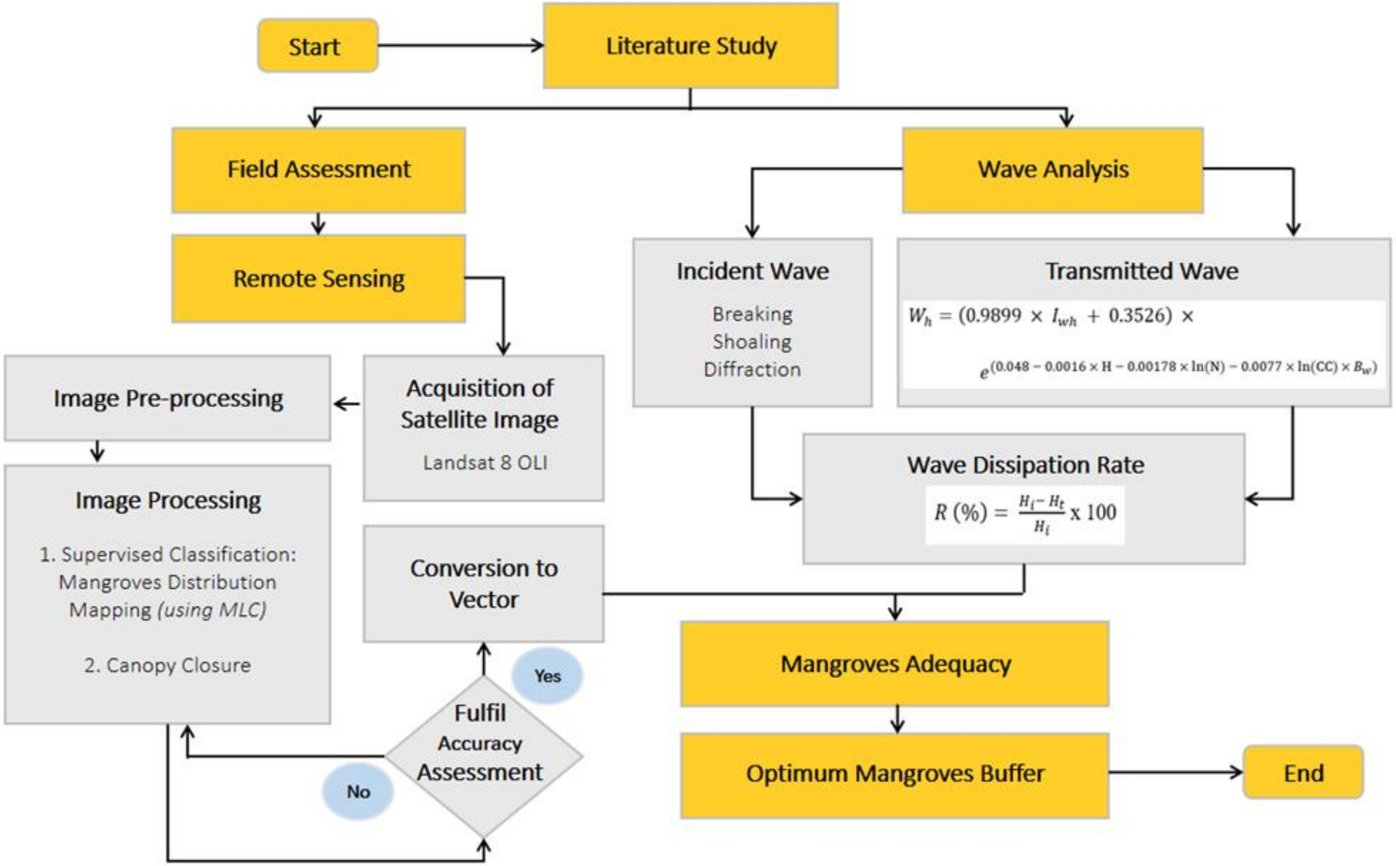


Figure 3.15: Research flowchart

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

Chapter 4 documents the results that serve as supportive evidence towards the achievement of the research objectives. A thorough discussion of the data obtained is also made in each sub-section. The mapping of land-cover in Kedah and mangrove distribution in the studied coastal areas are presented to fulfil the first objective. Aside from that, changes in the mangrove coverage recorded in two decades are further highlighted. This is followed by a discussion on wave dissipation analysis including wave transformation analysis for incident wave heights, transmitted wave heights, and assessment of wave reduction performance, which covers the second objective. The last section describes the last objective on mangrove adequacy assessment, along with the required replantation for optimum coastal protection.

4.2 Land-Cover Distribution Map in Kedah using GIS and Remote Sensing

Kedah land-cover map in Figure 4.1 shows the agriculture field as the largest land-cover among other classes with the percentage and area of 49.1% and 468,817.36 ha, respectively. The second highest land-cover is forest, followed by the build-up and inland water. However, mangroves contribute to the least coverage of land-cover. Details of areas and percentages of the respective classes are tabulated in Table 4.1.

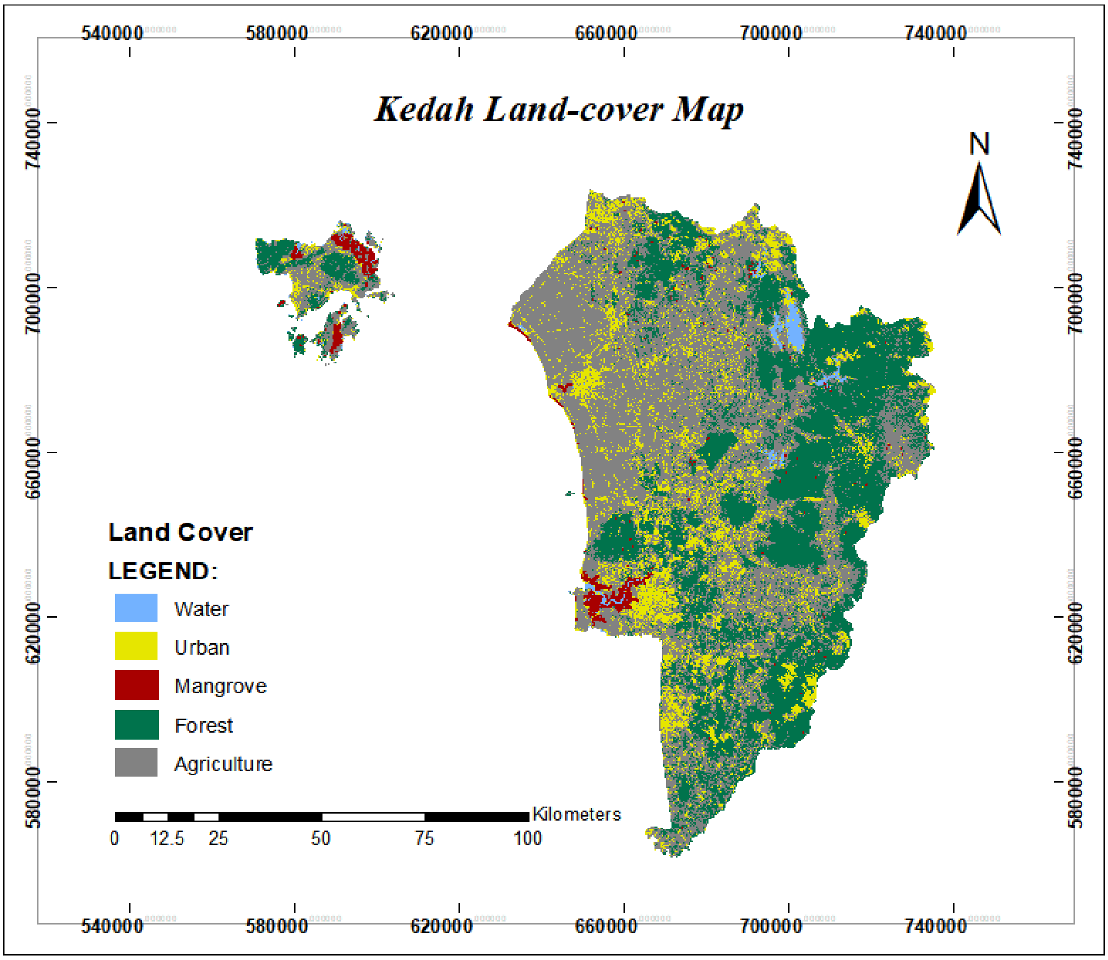


Figure 4.1: Kedah land-cover map

Table 4.1: Area of each class of land-cover

Class	Area, ha	Percentage, %
Water	9,824.09	1.0
Build-up	146,470.15	15.3
Mangrove	5,568.12	0.6
Forest	324,671.91	34.0
Agriculture	468,817.36	49.1

The agriculture field mainly consists of paddy field and other vegetations such as palm oil, rubber plantation, and coconut trees. Kedah is well-known for its scenic paddy field that it was named *"Jelapang Padi"* state after the massive paddy cropland. Besides, Kedah is also one of the most important rice producers and suppliers in Malaysia. As illustrated in Figure 4.2, the agriculture field, especially paddy cropland is quite abundant in the studied districts.

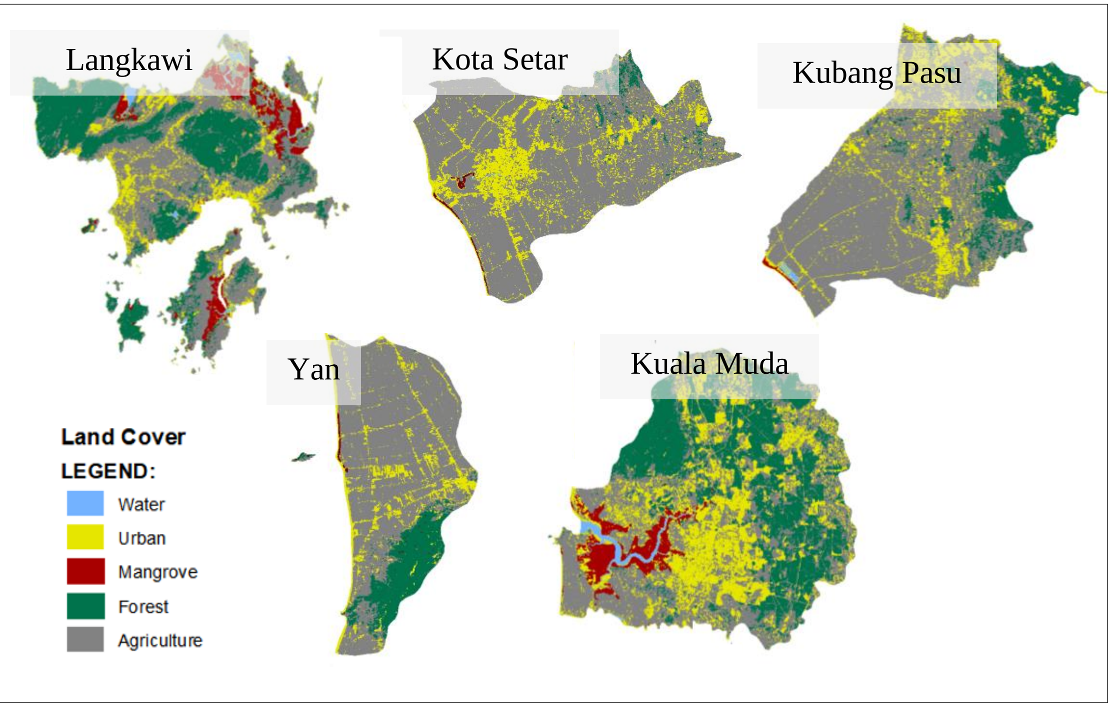


Figure 4.2: Land-cover in coastal districts

Merely 0.6% of mangroves were found in Kedah, which corresponds to an area of 5,568.12 ha. This reveals a loss of approximately 2,273.13 ha of mangroves coverage compared to 2012 [12]. A more detailed explanation of mangrove distribution is discussed in Section 4.2. In the west coast region of Peninsular Malaysia, Perak is acknowledged for its high distribution of mangroves that spreads over a wide area, especially in Matang or best known as Matang Mangrove Forest Reserve (MMFR) [9].

Aquaculture ponds are detected in Kubang Pasu and Kuala Muda mangrove areas. Based on Figure 4.1, aquaculture ponds are classified as inland water rather than distinguished separately as inland water and aquaculture. Hence, the GIS processing could not delineate between these two classes successfully. The development of aquaculture ponds is also seen as the biggest threat to the mangrove ecosystem. In common cases, mangroves are cleared to make room for aquaculture activities.

4.2.1 Validation of Land-Cover Map

A confusion matrix (or error matrix) is shown in Table 4.2. The matrix was developed to evaluate the accuracy of the land-cover classification. The accuracy validation includes the user's accuracy and total producer's accuracy for each category. The classified data were compared with 43 points observed from the ground-truth data, which leads to an overall accuracy of 93.02%.

Table 4.2: Confusion matrix for supervised classification

	Actual Category Classified						
Classified Category	Water	Urban	Mang-rove	Forest	Agri-culture	**Total**	**User's Accuracy, %**
Water	4	1	0	0	0	5	80.00
Urban	0	11	0	0	0	11	100.00
Mangrove	0	0	12	3	0	15	80.00
Forest	0	0	0	2	0	2	100.00
Agriculture	0	0	0	0	10	10	100.00
	4	12	12	5	10	**43**	
Total Producer's Accuracy, %	100.00	91.67	100.00	40.00	100.00		

4.3 Mangrove Distribution in Kedah using GIS and Remote Sensing

Figure 4.3 illustrates Kedah's mangrove coverage map, which indicates that dense mangroves are growing along Merbok River, Kuala Muda and Ayer Hangat, Langkawi. In most other districts, mangroves are distributed in sparse to medium density with low band width as measured from the coastline and the total mangrove area is 5,568.12 ha. In 2012, 7841.25 ha of mangroves was discovered [12] but only found in Langkawi, Kota Setar and Kuala Muda district. The distribution of mangroves in 2012 is depicted in Figure 4.4.

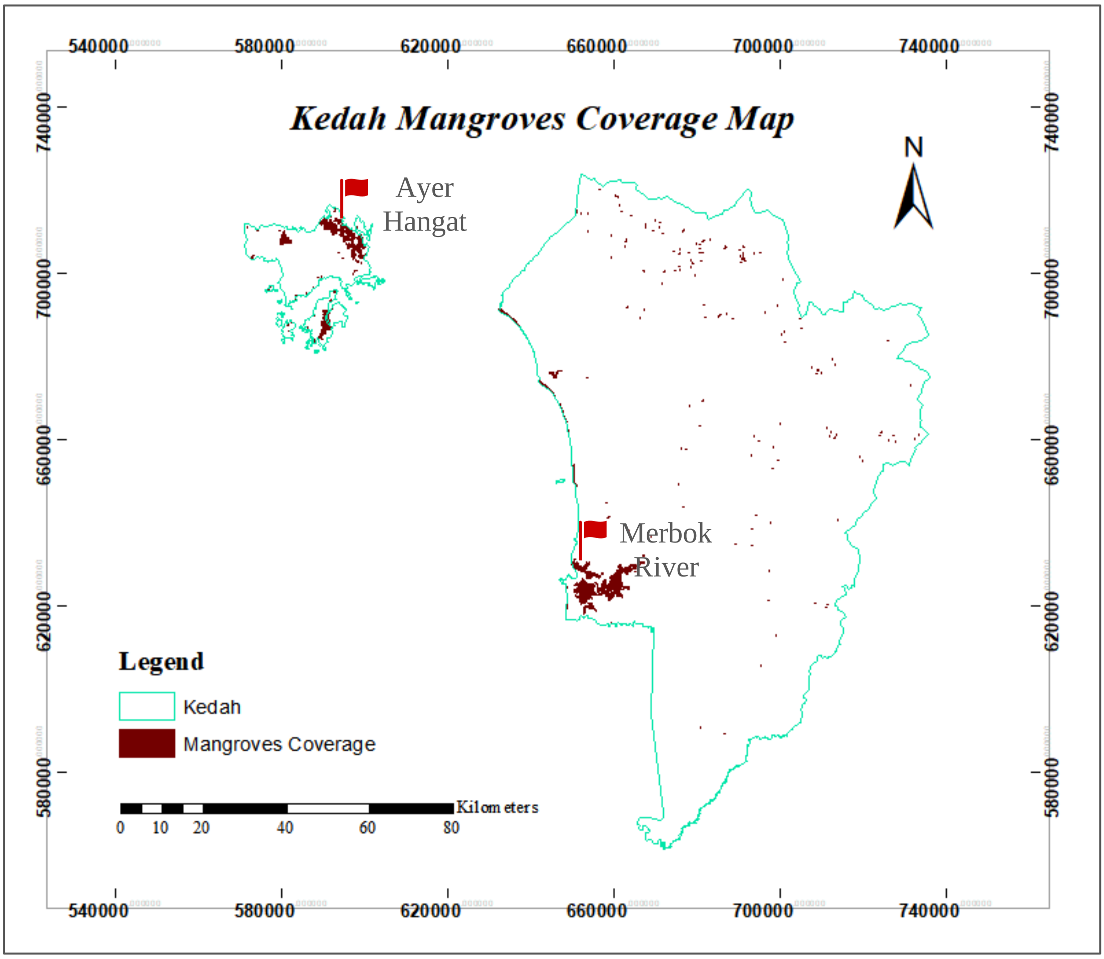


Figure 4.3: Mangrove distribution in Kedah

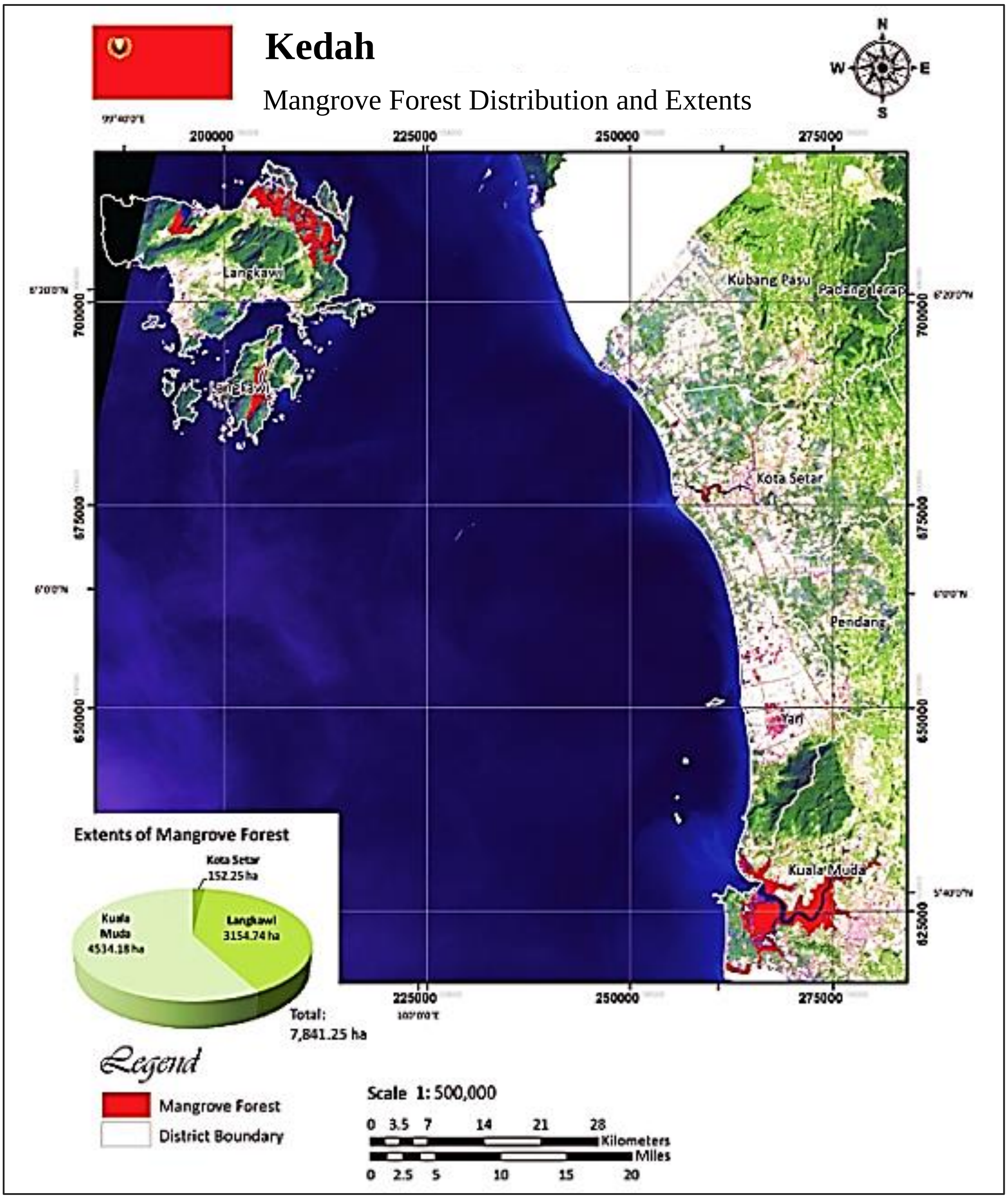


Figure 4.4: Kedah's mangrove distribution in 2012 [12]

Due to the medium-resolution satellite images opted, some sparsely distributed mangroves stretching in the fringe coastal areas could not be fully captured and classified as mangroves during the GIS classification process. Some of the mangroves even appear as agricultural land. This is most probably related to the spectral reflectance and tone image of mangroves that nearly resemble the agricultural land. Therefore, high-resolution satellite images will assist in producing more accurate mapping.

Field assessment revealed five species from two families of mangroves at the sites surveyed in this study, namely *Rhizophora apiculata*, *Avicennia marina*, *Rhizophora mucronata*, *Avicennia officianalis*, and *Avicennia alba*. Table 4.3 depicts the mangrove species discovered during field assessment and ground-truthing, where these data do not represent the overall species distribution in Kedah. *Avicennia marina* is the most abundant species that grows at each site. Meanwhile Kuala Kedah has the most variety species of mangroves.

Table 4.3: Species of mangrove found during field assessment and ground-truthing

District	**Location**	***R. apiculata***	***R. mucronata***	***A. marina***	***A. officianalis***	***A. alba***
Langkawi	Kuala Teriang	/		/		
	Sungai Melaka			/		
Kubang Pasu	Jerlun		/	/		
Kota Setar	Kangkong			/		
	Kuala Kedah			/	/	/
Yan	Sungai Daun			/	/	
Kuala Muda	Kuala Muda			/		
	Merbok			/		

* *R* corresponds to *Rhizophora*
** *A* corresponds to *Avicennia*

Detailed characteristics and species of mangroves at the studied site can be found in Appendix A. Based on the analysis, the *Avicennia* species mostly dominated the frontal areas, while the *Rhizophora* species are mostly growing at the estuaries, along the rivers and landwards.

This shows a parallel finding of mangroves zonation with Roslani et al. [130] in their study at Matang, Perak. According to their common zonation, the *Avicennia* species usually occur as the pioneer species and have the characteristics to tolerate high salinity. However, unlike the *Avicennia* species that abundantly grow seawards, the *Rhizophora* species, on the other hand, are mostly found landwards [142]. *Rhizophora* species are also dominant in the frequently flooded area of normal high tides.

Figure 4.5 and Figure 4.6 present the profile of common mangroves zonation in Peninsular Malaysia and Malaysia, respectively. As can be seen, *Avicennia* species colonizes the seaward fringe area, followed by *Sonneratia*, and *Rhizophora* while *Bruguiera* is occurring in the most landward area. All studied sites that are located along the Kedah coastline therefore explains the dominant of *Avicennia* species found throughout the site assessment.

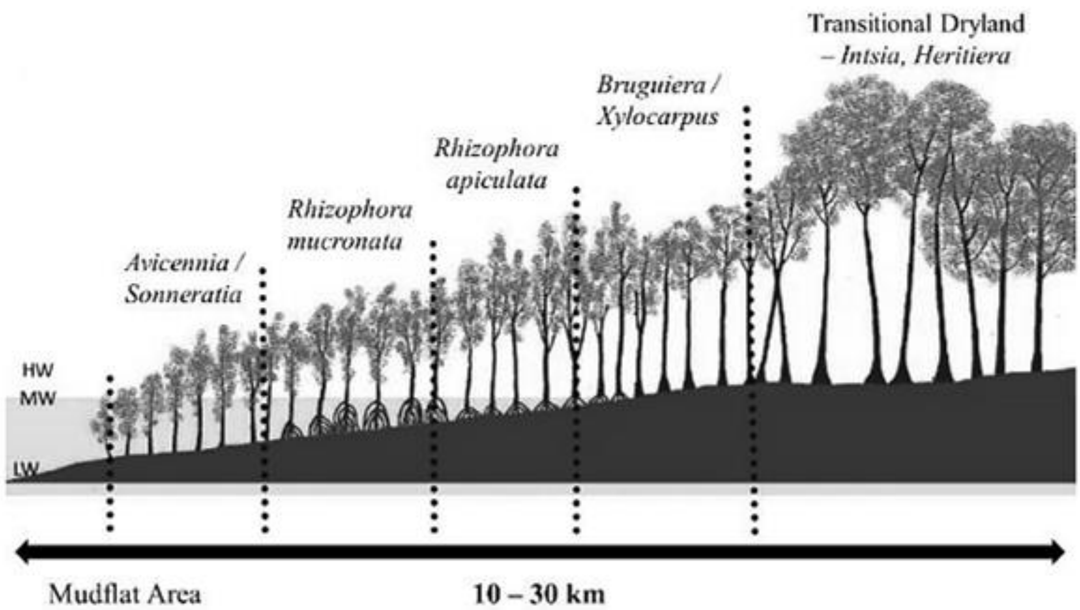


Figure 4.5: Typical zonation of mangroves along the land-sea interface in Peninsular Malaysia [143]

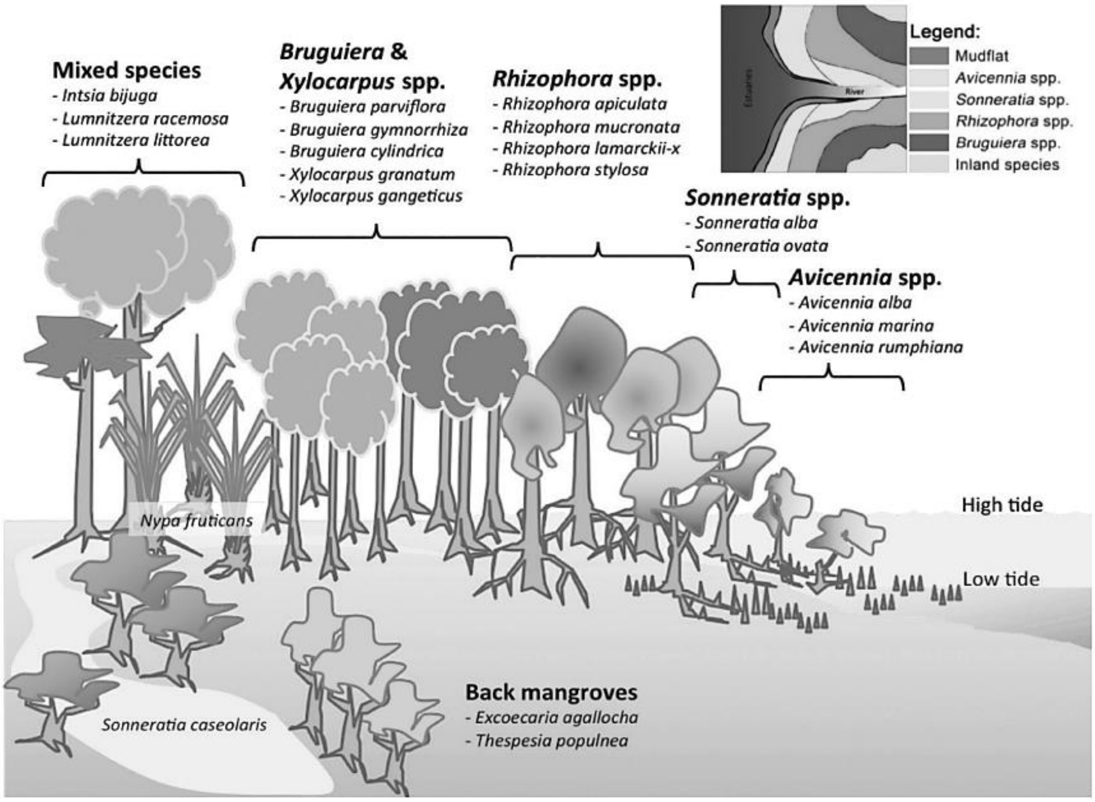


Figure 4.6: Typical mangrove zonation in Malaysia [12]

4.3.1 Mangrove Distribution Mapping in Kedah Coastal District

The detailed distribution and condition of each district are mapped in the following sub-sections.

4.3.1.1 Mangrove Distribution in Langkawi District

Mangroves in Langkawi spread densely in Ayer Hangat; some extent of mangroves could also be found colonizing in Kubang Badak, Pulau Dayang Bunting, and Pulau Tuba (see Figure 4.7).

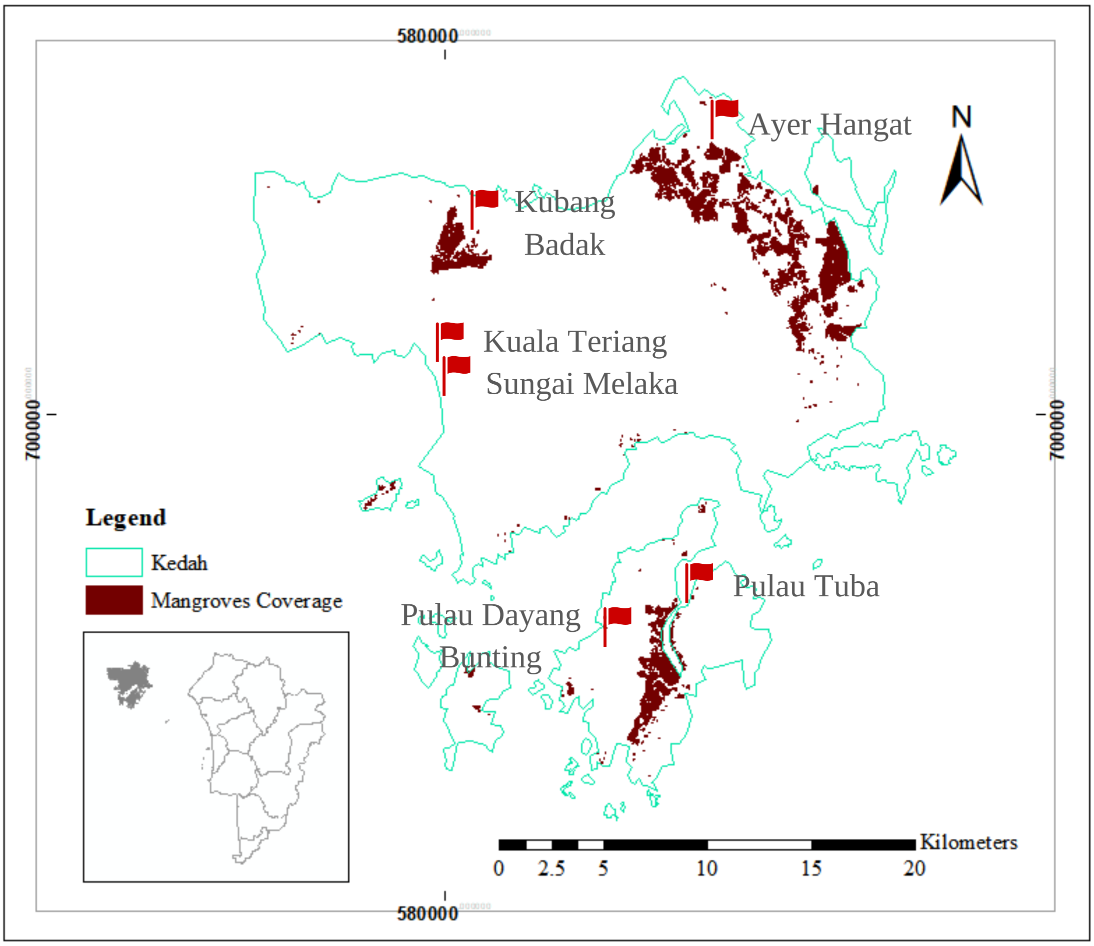


Figure 4.7: Mangrove distribution in Langkawi District

Besides, the Kilim Karst Geoforest Park, which is located in Ayer Hangat is part of the UNESCO Global Geoparks Networks (GGN) populated by mangroves. This geoforest park is conserved as an eco-tourism spot attraction in Langkawi. Most of the dominant mangrove species are *Rhizophora*. A boat tour around the Kilim Geoforest Park presents not only the sprawling mangrove swamp but also a variety of coastal habitats in the ecosystem such as monkeys, crab trees, monitor lizards, and eagles.

Kuala Teriang is one of the areas hit by the 2004 IOT. Field assessment was conducted there as well as in Sungai Melaka. In Kuala Teriang, the mangrove density increases landwards with some occurrences of *Rhizophora*; however, the density is still quite sparse. The *Avicennia* species were also abundant in this area. Besides, some bamboos were found on the ground, and it is believed that replantation has previously taken place using bamboos as the replantation method technique. Replantation in Kuala Teriang has been initiated since 2005 and deemed successful whereby healthy mangroves were found growing at the site [144].

In Sungai Melaka, the mangrove density is low and getting denser as it approaches the estuary of Sungai Melaka. The species entail a combination of *Avicennia* and *Rhizophora*. As shown in Figure 4.8, a layer of sand covers some part of the muddy area at the site. This could be one of the factors causing the lower distribution of mangroves whereby the site condition is unsuitable for mangroves that prefer the muddy area to thrive in. Aside from that, the sandy soil results in loose grips of the mangrove roots, substantially becoming less stable and eventually will topple down.

Figure 4.8: Site condition in Sungai Melaka

However, these two areas were not plotted in the mangrove coverage map. The lower distribution over low band width, sparse density, and younger trees might be the reasons that these areas were not captured during the classification process.

4.3.1.2 Mangrove Distribution in Kubang Pasu District

Figure 4.9 below demonstrates the coverage of mangroves in Kubang Pasu District. Mangroves were distributed very sparsely at the frontal area; however, a highly dense population was observed landwards.

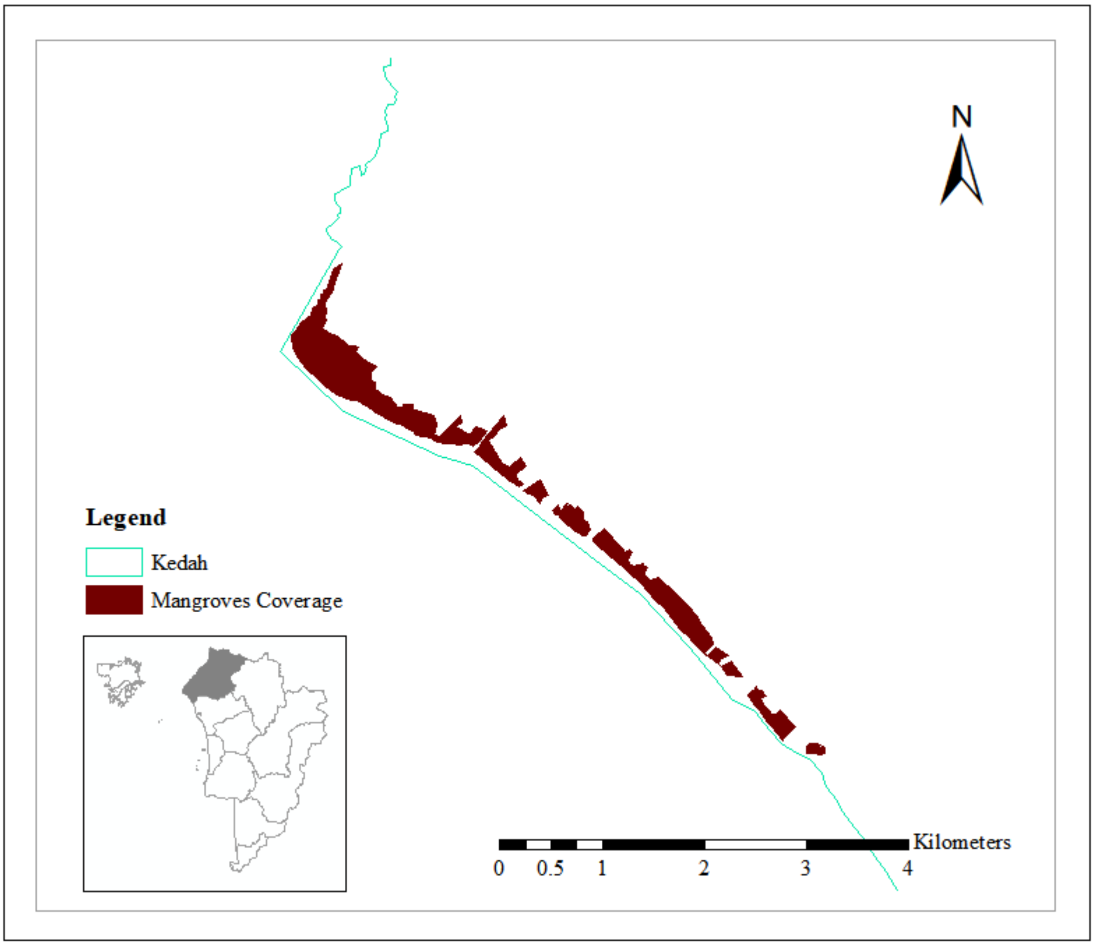


Figure 4.9: Mangrove distribution in Kubang Pasu District

The age of the frontier mangroves are about five years old, and the maturity increases as the band width increases landwards. The age of mangroves is usually associated with their height and diameter of trunks or roots, or generally the physical geometries. The identification of mangroves age can be referred to the Table 4.4.

Table 4.4: Geometry parameters for age identification of mangroves [139]

Geometry parameter	**Mature**	**Middle-age**	**Young**
Age of tree, year	>25	<8	0.8
Total height of tree, m	10.34	7	1.38
Height of roots, m	1.54	1.2	0.9
Height of trunks, m	1.8	1.5	-
Height of canopy, m	4.2	4.2	0.48
Diameter of trunk, m	0.2	0.09	0.03
Diameter of roots, cm	1.0 – 9.0	1.0 – 3.5	0.02
Diameter of branches, cm	1.5 - 15	0.5 – 1.5	0.5
Width of roots, m	5.6	3	0.98
Width of canopy, m	7	3	0.6
Number of branches	24	24	8

Meanwhile, at the assessed site in Jerlun, most of the mangrove leaves were defoliated during the visit. The most obvious finding, however, was the abundant number of prawns and fishponds found near the mangrove area. This is expected [145, 116, 5, 146] because the mangrove environment is suitable for aquaculture activities. Besides that, this aquaculture activities have becoming one of the largest threats resulting to the declination of mangroves coverage.

4.3.1.3 Mangrove Distribution in Kota Setar District

In the Kuala Kedah area (as marked in Figure 4.10), mangroves of young, middle-aged, and matured trees were found. Mangrove occurrence was spotted in the Kedah River area and the mangroves fringing the coast have a density range from moderately dense to high dense, getting denser from the frontal area landwards. Meanwhile, Kangkong has a very low band width of mangrove band. Middle-age mangroves grow with sparse density population and most of the species found were *Avicennia*.

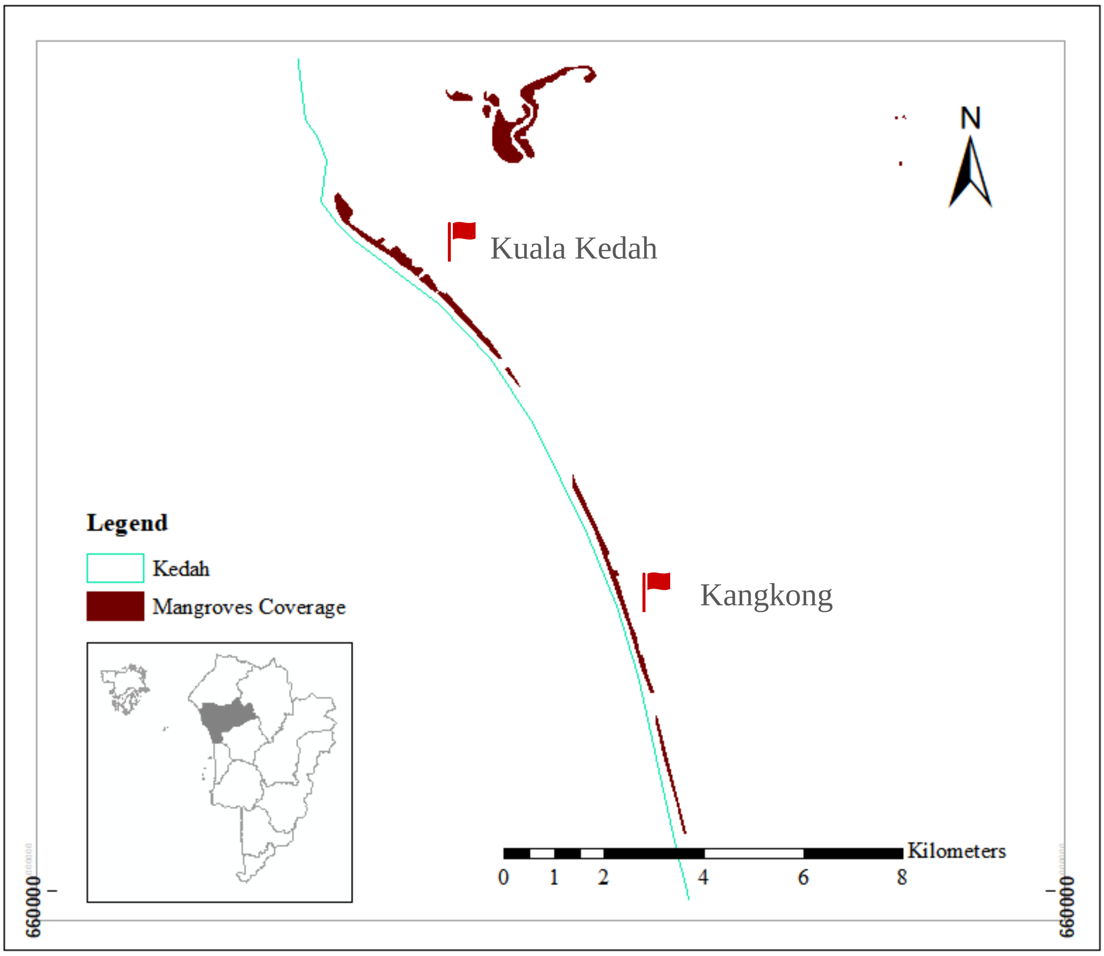


Figure 4.10: Mangrove distribution in Kota Setar District

Additionally, it was also observed that some parts of the mangrove area in Kuala Kedah might have undergone mangrove clearance, perhaps for development. As depicted in Figure 4.11, the area stands between two densely populated mangroves and is believed to have been cut down earlier.

Figure 4.11: Clearance of mangroves in Kuala Kedah

4.3.1.4 Mangrove Distribution in Yan District

Figure 4.12 illustrates the extent of mangroves in Sungai Daun, Yan. A tall and high density of mangroves were observed with some small and middle-aged mangroves thriving at the frontier of the coastline. However, the density of the young and small mangroves is not as dense as the taller mangroves growing backwards. *Avicennia*, as expected, is among the species inhabiting this fringe coastal area. A small island called Pulau Bunting is located approximately 2 km from the coastline of Sungai Daun. Sea waves will, thus, diffract as they pass through the lee side of the small island.

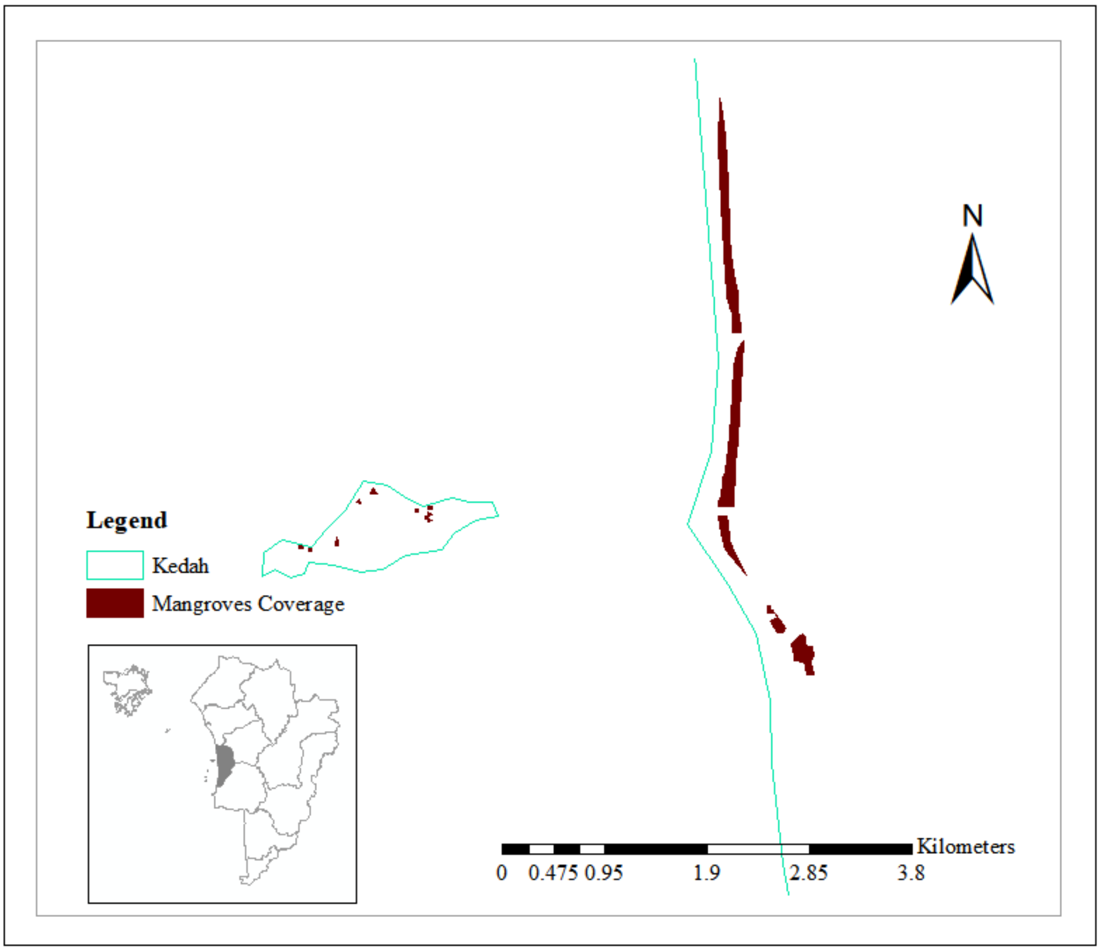


Figure 4.12: Mangrove distribution in Yan District

4.3.1.5 Mangrove Distribution in Kuala Muda District

Mangrove distribution in Kuala Muda District is depicted in the following Figure 4.13, comprising Merbok and Kuala Muda areas. Merbok's mangroves have been gazetted under the Permanent Reserve Forest (PRF), known as Merbok Mangrove Reserve. Merbok is rich in species diversity with 30 species recorded [147], but in 2012, only a total of 23 species was discovered in Merbok PRF [12]. Nonetheless, both are less diverse than Langkawi with 32 exclusive mangroves over the total 76 mangrove species [148].

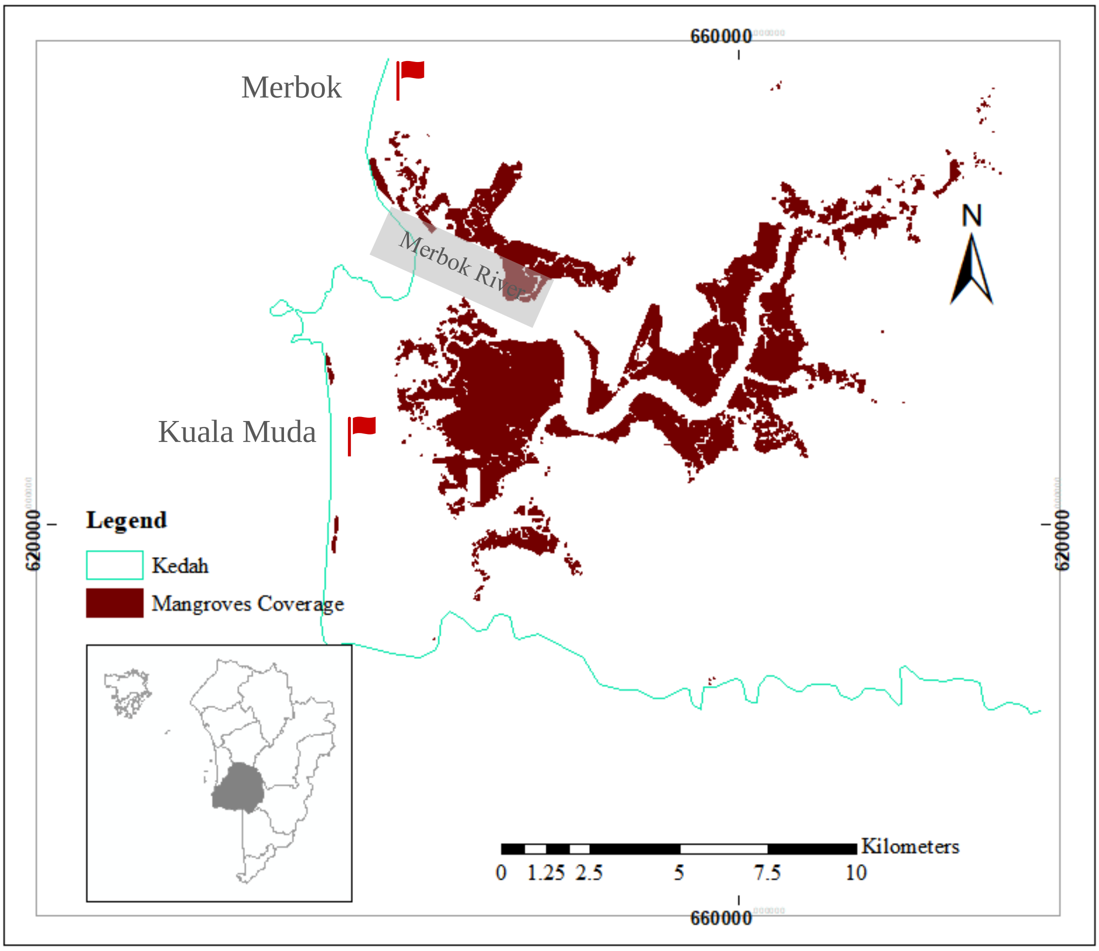


Figure 4.13: Mangrove distribution in Kuala Muda District

During the field assessment, the mangroves found were mostly matured and tall. *Avicennia* is the most dominant species distributed throughout the forest along the coastline. Other than that, scarp formation was observed where the mud has been slowly eroded at a great depth. The sand can also be seen covering the intertidal zone just before the muddy part, while many mangrove trunks were seen toppling to the ground at the frontier part due to instability caused by scouring. Aside from the eroding mud, severe wave conditions could also contribute to the scour (see Figure 4.14).

Figure 4.14: Scarp formation in Merbok

In Kuala Muda, the mangroves stretching along the coastline were low and only small patches of mangroves were observed in Kampung Sungai Yu and Kampung Padang Salim. Some other low distributed mangroves along this coastline were not plotted on the map, for instance, in Kampung Masjid and Kampung Paya. This is perhaps due to the sparse density and the medium-resolution satellite images used.

Based on a previous study [149], Kampung Masjid was among the most affected in the Kuala Muda area during the 2004 IOT. However, Kampung Sayak that is located northern to Kampung Masjid experienced fewer damages due to the dense mangroves fringing the area. The tsunami victims, according to one of the villagers, were moved to Permatang Katong, which was built as the permanent relocation houses for the tsunami victims [150].

4.3.2 Mangrove Changes in Kedah

Over decades, Kedah has experienced changes and losses of mangrove extent. The degradation was mainly caused by anthropogenic factors such as clearance for aquaculture activity, urban development, coastal erosion, and agriculture purposes [12]. Table 4.5 shows the mangrove areas recorded in the years 2000 [11], 2012 [12], and 2020 as in the current study. The losses detected over two decades are approximately 2,754.57 ha or 33.1% and this explains that the degradation occurs at an alarming rate.

Table 4.5: Mangrove coverage and losses in Kedah

Mangrove Coverage in 2000 – 2020, ha			**Mangrove Losses**	
2000 [11]	**2012** [12]	**2020**	**ha**	**%**
8,322.79	7,841.25	5,568.12	2,754.67	33.1

Several changes were detected from Google Earth in Figure 4.15, showing changes in the land-cover, especially between 1990 and 2000 where many aquaculture ponds were developed over the destroyed mangroves near Merbok River.

Figure 4.15: Mangrove coverage in Merbok in (a) 1990, (b) 2002, (c) 2013, and (d) 2020.

Mangrove stretch at the south of Kuala Muda bordering Pulau Pinang is another part that has undergone degradation. The current condition, as observed from Google Earth, revealed only small patches of mangroves inhabiting the area. Urbanization has taken place and destroyed the wide spread of mangroves to make room for development. This includes the development of Taman Permatang Katong in the area as one of the government actions to relocate the victims affected during the 2004 tsunami as claimed by the community.

4.3.3 Summary of Mangrove Distribution in Kedah

The advanced technology of GIS and remote sensing has enabled the detection of mangrove distribution and its total area. The calculated areas include those of other districts than the five studied districts, grouped as “Others” in Table 4.5. The length of the coastline mapping covered and uncovered with mangroves, analyzed from the GIS mapping have also been presented. However, no mangrove was recorded along the coastline of the Langkawi region exposed to the wave direction, probably due to the sparse density and low population. Since the “Others” districts are of a non-coastal area, thus, no coastline was measured.

Table 4.5: Summary of mangrove coverage in Kedah

District	Area of Mangrove, ha	Length of Mangrove along Coastline, km	Length of Mangrove-free Coastline, km
Langkawi	2,068.01	N/A	67.16
Kubang Pasu	118.01	5.90	4.89
Kota Setar	166.26	12.09	12.50
Yan	36.74	4.81	24.68
Kuala Muda	3,287.35	3.18	12.65
Others	58.01	N/A	N/A
TOTAL	**5,568.12**	**25.98**	**121.88**

4.4 Wave Analysis along the Kedah Coastline

The wave analysis in this study revolves around two wave heights that consist of incident wave height and transmitted wave height. Incident wave height is defined as the height of incoming wave before hitting the mangrove forest, while the transmitted wave height refers to the height of wave after propagating into the mangrove forest.

4.4.1 Incident Wave Heights

The wave height in Kedah ranges from 0.5 m to 2 m as indicated by the Department of Irrigation and Drainage (DID), Malaysia within the year 1949 to 1989. An extreme wave height of 5.5 m was recorded; however, this only appeared once in the listed data probably due to some technical error or seasonal effect; hence, a 2 m wave height was considered the highest [151]. A significant wave height of 0.99 m was obtained from an average of the highest one-third of the wave height over 40 years. Besides, an average wave period of 5.46 s with the corresponding wave direction of 290º were recorded in the collected data of 276 datasets. Table 4.6 presents the significant wave height and the heights of waves as the waves travel shoreward, changing over water depth and undergoing transformation. Appendix C is referred for complete calculation.

Table 4.6: Wave transformation analysis

District	**Location**	**Significant Wave Height, m**	**Height of Wave, m**	
			Shoaling	**Refraction**
Langkawi	Kuala Teriang	0.99	1.01	0.85
	Sungai Melaka	0.99	1.01	0.85
Kubang Pasu	Jerlun	0.99	1.05	0.92
Kota Setar	Kangkong	0.99	1.02	0.87
	Kuala Kedah	0.99	1.02	0.87
Yan	Sungai Daun	0.99	1.05	0.92
Kuala Muda	Kuala Muda	0.99	1.03	0.89
	Merbok	0.99	0.99	0.83

The wave heights increased when shoaling occurred in the changing of bathymetry. This is because wavelength decreases as the wave speed reduces; thus, to conserve the same amount of energy, the wave height increases [152]. The highest shoaling wave heights were calculated in Jerlun and Sungai Daun. When the waves further underwent refraction, the heights were reduced due to the spread of waves over a larger distance, with Sungai Daun and Jerlun having the highest refracted wave heights. The shoaling wave height varies according to the depth at each location, which also causing some locations received more wave refraction than others. For further analysis, the value of shoaling wave height was taken as the incident wave height, H_i, considering the highest wave amplitude which would result to worst-case scenario.

4.4.2 Transmitted Wave Heights

In this study, the wave heights after passing through the mangroves were analyzed using Bao's formula (refer to Equation 3.3). The relation of mangrove geometries, mangrove band widths, densities, and wave heights were all incorporated in obtaining the formula. This fills the gaps of other studies that mostly focus on only one affecting factor in studying the attenuation by mangroves. Besides, the formula was developed by considering all types of mangrove species instead of solely on mono-species like most other studies and, thus, would be more relevant and applicable to all cases.

Bao has been successful in proving the high accuracy of the theoretical value for the wave height reduction with the experimental value obtained from the Vietnam coastline. The details of the average mangrove height, mangrove density, and canopy closure for each location assessed in the current study are depicted in Table 4.7. Mangrove heights and density were both obtained from the field assessment, while the other parameters were computed using GIS tools and Geoprocessing. Complete calculation and analysis can be found in Appendix D.

Table 4.7: Mangrove detailing at respective locations

District	**Location**	**Average Tree Height, m**	**Tree Density, tree/ha**	**Canopy Closure, %**
Langkawi	Kuala Teriang	1.65	890	N/A
	Sungai Melaka	1.80	920	N/A
Kubang Pasu	Jerlun	3.70	8,600	75
Kota Setar	Kangkong	2.65	3,700	63
	Kuala Kedah	6.80	11,800	85
Yan	Sungai Daun	5.35	7,800	77
Kuala Muda	Kuala Muda	4.65	3,400	68
	Merbok	5.65	5,500	75

Figure 4.16 shows the transmitted wave height based on the initial wave height over the mangrove forest band width for each location. Overall, the coastline of Kedah is long, and each location differs in terms of mangrove band width, average tree height, and the number of trees per hectare. However, taking the average of the band width might not be accurate and might not represent the mangrove forest characteristics well because some parts have greater band widths than others. Therefore, mangrove band widths ranging from minimum to maximum were assessed to better represent the mangrove forest characteristics.

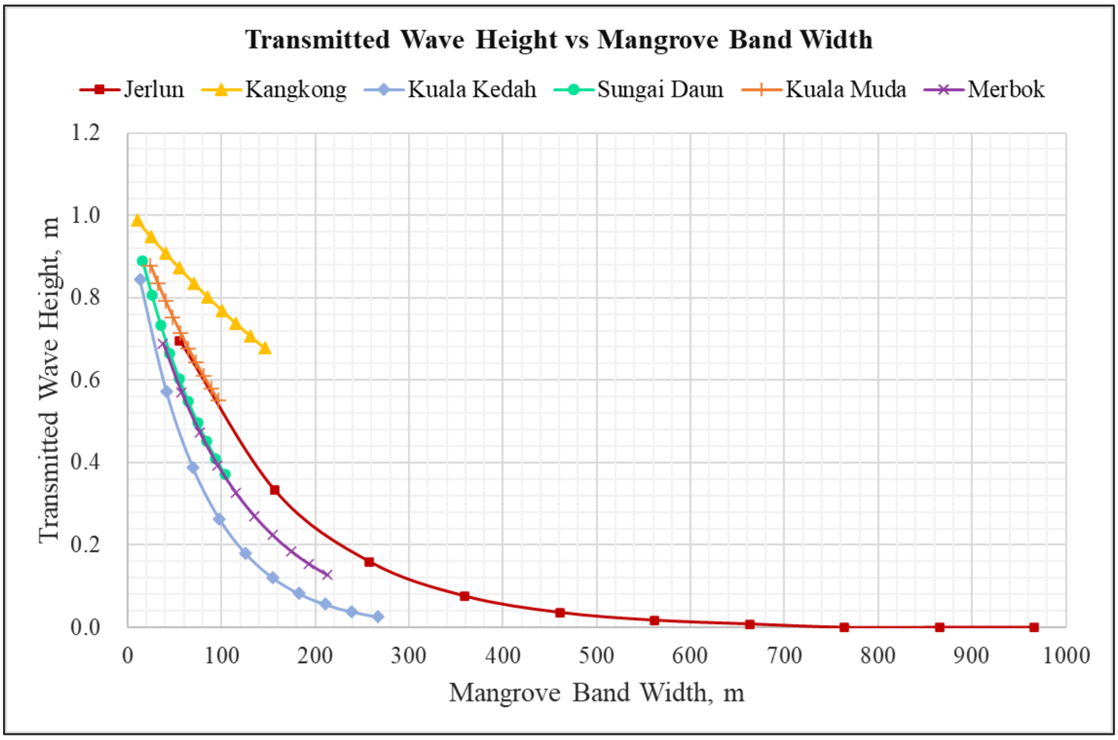


Figure 4.16: Transmitted wave heights over mangrove band widths

Besides, a decreasing pattern can also be observed in the relationship between transmitted wave heights and mangrove band widths in all locations. Evidently, transmitted wave heights in mangroves reduced with intensified band widths of the forest. While less transmission occurred in Kangkong, Jerlun, however, marked the greatest transmission. Kangkong represented the lowest band width of all sites, which also clarifies that greater waves might be transmitted if the band width is greater. However, the band width alone is not the main reason for such reduction. This is also subjected to the mangrove characteristics at each location, which play their own role in decreasing the wave magnitude.

In the transmitted wave analysis, the values for the Langkawi sites in both locations were not analyzed due to the lack of data from the previous GIS analysis. No mangroves were recorded and graphed in GIS mapping at the studied locations, which might be due to the low mangrove coverage or medium-resolution satellite images that were unable to capture any distribution as previously explained in Subsection 4.2.3. Thus, the calculation for transmitted waves could not be done since no canopy closure data were produced for the studied locations. From this point onwards, the Langkawi sites may not be included in the discussion.

4.4.3 Wave Reduction by Mangroves

Table 4.8 depicts the reduction rate of mangrove over mangrove band width. Wave reduction was calculated by applying the formula in Equation 3.4. The reduction performance was further assessed based on the greatest reduction rate yielded by each site.

Table 4.8: Reduction rates of mangrove vs mangrove band widths

Jerlun		**Kangkong**		**Kuala Kedah**	
Band Width, m	**Reduction Rate, %**	**Band Width, m**	**Reduction Rate, %**	**Band Width, m**	**Reduction Rate, %**
55.5	33.4	10.0	3.1	13.5	17.3
156.7	68.2	25.1	7.1	41.7	43.9
257.9	84.8	40.2	10.9	69.8	61.9
359.2	92.7	55.3	14.5	98.0	74.2
460.4	96.5	70.4	18.0	126.2	82.5
561.6	98.3	85.6	21.4	154.3	88.1

Table 4.8: Reduction rates of mangrove vs mangrove band widths (continued)

Jerlun		Kangkong		Kuala Kedah	
Band Width, m	**Reduction Rate, %**	**Band Width, m**	**Reduction Rate, %**	**Band Width, m**	**Reduction Rate, %**
662.8	99.2	100.7	24.6	182.5	91.9
764.1	100.0	115.8	27.7	210.7	94.5
865.3	100.0	130.9	30.6	238.8	96.3
966.5	**100.0**	146.0	**33.5**	267.0	**97.5**

Sungai Daun		Kuala Muda		Merbok	
Band Width, m	**Reduction Rate, %**	**Band Width, m**	**Reduction Rate, %**	**Band Width, m**	**Reduction Rate, %**
16.0	14.9	24.0	14.8	37.5	30.7
25.7	22.8	32.1	19.1	57.0	42.5
35.4	29.9	40.2	23.2	76.5	52.3
45.2	36.4	48.3	27.1	96.0	60.5
54.9	42.2	56.4	30.8	115.5	67.2
64.6	47.6	64.6	34.3	135.0	72.8
74.3	52.4	72.7	37.6	154.5	77.5
84.1	56.8	80.8	40.8	174.0	81.3
93.8	60.8	88.9	43.8	193.5	84.5
103.5	**64.4**	97.0	**46.6**	213.0	**87.2**

Jerlun indicated the best dissipation performance where the wave height was reduced to 0 m from the initial incident wave height of 1.05 m as it travelled through the maximum band width. The waves were fully attenuated when they reached a band width of 764.1 m. Furthermore, the mangrove forest has high density and canopy closure with the maximum band width reaching up to 966.5 m. Based on the recorded average tree height, the forest is also dominated by matured trees, and this becomes the possible driving factor for the greatest wave reduction performance of mangroves.

The great mangrove structures gave Jerlun an extra point in dissipating more waves. The high forest density with more obstruction from roots due to vegetation that grows closely to each other also causes less space to travel and composes more friction drag. In such a scenario, the waves are most probably attenuated and lose their energy as they hit the mangroves' roots and trunks [44, 79, 16]. In a recent study, [62] concluded that the densely distributed *Rhizophora* dissipated effectively with an 81% dissipation rate compared to the sparsely populated mangroves with a dissipation rate of only 65%.

Another significant influential factor is the forest band width. As presented in Table 4.8, Kuala Kedah is rather competitive as Jerlun, making it the top two in attenuation performance with a dissipation rate of 97.5% over its maximum band width. However, the waves were not fully attenuated, and this is strongly related to the lower width compared to Jerlun. While a few more metres in band width would suggest a 100% attenuation, likewise, greater band width that leads to greater dissipation is an evident hypothesis. Extensive studies supporting this theory have been elaborated in Chapter 2.

However, Kangkong demonstrated the least wave height reduction of all. The low dissipation performance was stemming from the sparse tree density with low canopy closure as well as the low average tree height. Normally, a low tree height indicates younger mangrove trees with lower ability in withstanding wave actions [97]. As the trees get matured, the root and trunk diameters likewise increase and, thus, resulting in more attenuation performance [93]. Density also plays a great role whereby, in this case, the density is very low and, therefore, causing low dissipation. Evidently, the reduction rate by this forest with the respective characteristics was only 33.5%.

Next, a new set of data on wave reduction rates but over a similar range of mangrove band width was produced and interpreted in graphs as shown in Figure 4.17. The band width range was determined by choosing the highest minimum band width (55.5 m) and the lowest maximum band width (97.0 m); the range of which all the study sites lie within. The reason is to study the other forest characteristics when the band width is set as a controlled variable.

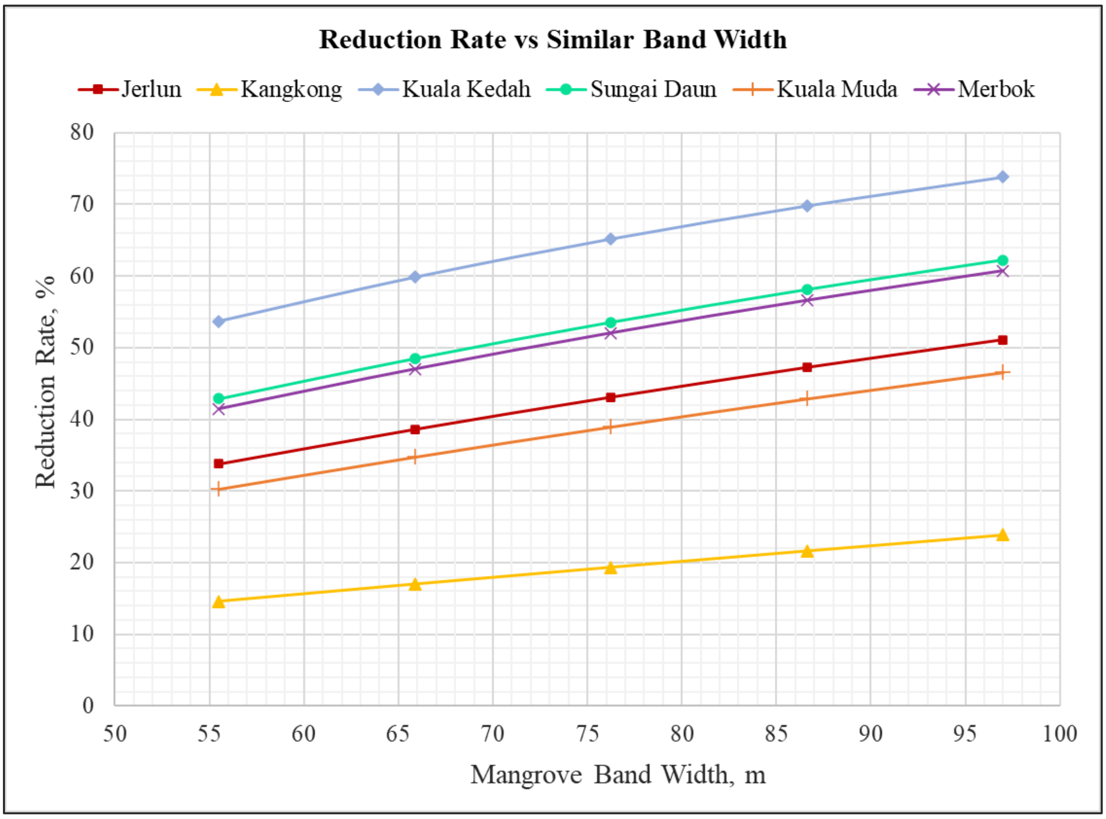


Figure 4.17: Reduction rates of mangrove over similar mangrove band width

What stands out in Figure 4.17 is that Kuala Kedah appears to have the highest dissipation performance rate of 73.8%, followed by Sungai Daun, Merbok, Jerlun, and Kuala Muda with dissipation rates of 62.2%, 60.7%, 51.1%, and 46.6%, respectively. Meanwhile, Kangkong has the lowest dissipation rate with 23.9%.

In the previous analysis, Jerlun showed the greatest performance in wave attenuation due to its widest band width. However, when assessed over similar band width, Kuala Kedah demonstrated better reduction at a 97 m width. Compared to Jerlun, mangrove characteristics in Kuala Kedah are also denser and have higher canopy closure. This points out that the waves might not be fully dissipated if the band width is inadequate, even if the forest is attributed to other good vegetation features. Therefore, the sufficiency of mangrove band widths should be estimated along with other mangrove structures so that enough protection can be guaranteed by the respective forest structures.

4.4.4 Comparison of Wave Reduction using Other Empirical Formula

Wave reduction calculated using Bao's formula was compared with a few empirical formulas from other studies to examine the similarity of wave reduction at the study sites and to verify the reliability of Bao's formula. Accordingly, Bao's formula was emphasized in this study due to its thorough analysis, which includes all wave attenuation factors by mangroves. Equation 2.4 and Equation 2.5 (also in reference to Ismail etc.'s in Table 4.10) were adopted to satisfy this purpose.

The analysis result using Equation 2.4 demonstrates a conflicting outcome. Although mangrove width is claimed to have a linear relationship with the wave attenuation in their study, their function for wave attenuation is not reliable. Table 4.9 shows a contradictory analysis where the attenuation ability of mangroves declined with the increasing band width. Jerlun denotes the widest minimum band width among all sites that obtained the lowest attenuation performance, whereas the circumstance is vice versa for Kangkong.

Table 4.9: Attenuated wave vs mangrove width using Equation 2.4

Location	Minimum band width (m)	Attenuated wave (m)
Jerlun	55.5	-53.00
Kangkong	10.0	0.78
Kuala Kedah	13.5	-0.12
Sungai Daun	16.0	-1.10
Kuala Muda	24.0	-6.06
Merbok	37.5	-20.83

Figure 4.18 depicts the wave attenuation analyzed using Ismail etc.'s formula. A similar increasing pattern of wave reduction across the mangrove band width as Bao's formula was observed. This proves that wave dissipation increases with the increase in mangrove band width. Jerlun presents the highest attenuation, whereas Kuala Muda marks the lowest. The attenuation performance for locations other than Jerlun and Sungai Daun might barely can be seen in Figure 4.18, hence Table 4.10 is referred to.

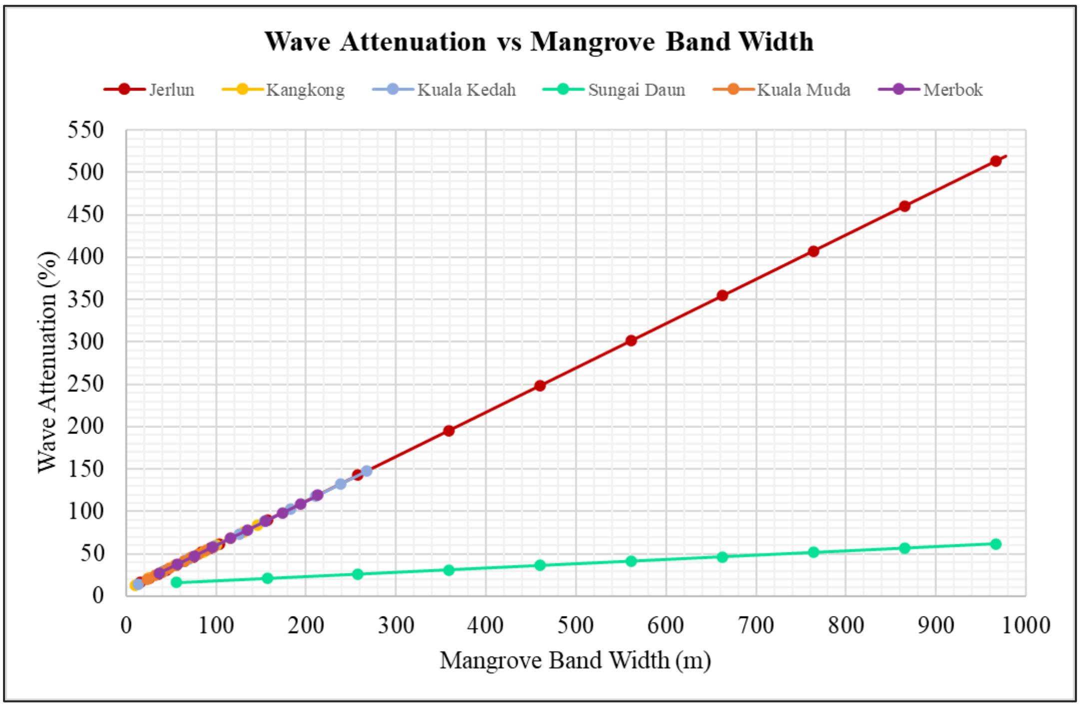


Figure 4.18: Wave attenuation vs mangrove band width using Ismail etc.'s formula

Table 4.10: Comparison of reduction rate using Bao's and Ismail etc.'s formula

Jerlun			Kangkong		
Width, m	Reduction Rate, %		Width, m	Reduction Rate, %	
	Bao's	Ismail etc.'s		Bao's	Ismail etc.'s
55.5	33.8	36.6	10.0	3.1	12.8
156.7	68.3	89.6	25.1	7.1	20.7
257.9	84.9	**142.5**	40.2	10.9	28.6
359.2	92.8	**195.5**	55.3	14.6	36.5

Table 4.10: Comparison of reduction rate using Bao's and Ismail etc.'s formula (continued)

Jerlun			Kangkong		
Width, m	Reduction Rate, %		Width, m	Reduction Rate, %	
	Bao's	Ismail etc.'s		Bao's	Ismail etc.'s
460.4	96.5	**248.5**	70.4	18.1	44.4
561.6	98.3	**301.4**	85.6	21.4	52.3
662.8	99.2	**354.4**	100.7	24.6	60.2
764.1	100.0	**407.4**	115.8	27.7	68.1
865.3	100.0	**460.3**	130.9	30.7	76.0
966.5	100.0	**513.3**	146.0	33.5	84.0

Kuala Kedah			Sungai Daun		
Width, m	Reduction Rate, %		Width, m	Reduction Rate, %	
	Bao's	Ismail etc.'s		Bao's	Ismail etc.'s
13.5	17.3	14.6	16.0	15.4	15.9
41.7	43.9	29.4	25.7	23.2	21.0
69.8	62.0	44.1	35.4	30.3	26.1
98.0	74.2	58.8	45.2	36.7	31.2
126.2	82.5	73.6	54.9	42.5	36.3
154.3	88.1	88.3	64.6	47.8	41.4
182.5	91.9	**103.1**	74.3	52.7	46.4
210.7	94.5	**117.8**	84.1	57.0	51.5
238.8	96.3	**132.5**	93.8	61.0	56.6
267.0	97.5	**147.3**	103.5	64.6	61.7

Table 4.10: Comparison of reduction rate using Bao's and Ismail etc.'s formula (continued)

Kuala Muda			Merbok		
Width, m	Reduction Rate, %		Width, m	Reduction Rate, %	
	Bao's	Ismail etc.'s		Bao's	Ismail etc.'s
24.0	14.7	20.1	37.5	30.4	27.2
32.1	19.0	24.4	57.0	42.3	37.4
40.2	23.1	28.6	76.5	52.2	47.6
48.3	27.0	32.8	96.0	60.4	57.8
56.4	30.7	37.1	115.5	67.1	68.0
64.6	34.2	41.3	135.0	72.8	78.2
72.7	37.6	45.6	154.5	77.4	88.4
80.8	40.7	49.8	174.0	81.3	98.6
88.9	43.7	54.1	193.5	84.5	**108.8**
97.0	46.6	58.3	213.0	87.1	**119.0**

As can be observed in Table 4.10, the reduction rates produced from Ismail etc.'s formula were greater than Bao's formula, indicating a better reduction performance. Waves are fully dissipated in Jerlun, Kuala Kedah, and Merbok whereby the reduction rate surpassed 100%, as bolded. Kuala Muda with the lowest band width has the lowest attenuation performance with only a 58.3% reduction. Nevertheless, this overestimates the wave reduction rate or performance since only mangrove band width was incorporated into the analysis of reduction by mangroves.

The other vital attenuation factors such as the physical characteristics of mangroves were not considered in their formula, causing the analyzed value to be more intensified than the actual. Mangroves with a great band width may generate high wave reduction. But the high band width of mangroves with a sparse density could result in a different attenuation performance, which again highlights the importance to take into account each affecting attenuation factor in analyzing the performance of mangroves in dissipating waves.

4.5 Mangrove Adequacy in Wave Dissipation along the Kedah Coastline

Next, the current mangrove band widths were cross-checked with the minimum required band widths for mangrove adequacy determination. The minimum required band widths were calculated using Equation 3.5, which was previously explained in Chapter 3. Bao [8] developed the formula to calculate the adequate band width of mangroves for providing sufficient guard for the coastline, with consideration of different structures of mangroves and wave parameters.

Subsequently, the safe wave height behind the mangrove forest is accepted within the range of 0.3 m [9]. The wave height was set based on the observation at the site and interview with local people working in agriculture and aquaculture industry. Comparisons between the required and current band widths are illustrated in Table 4.11.

Table 4.11: Current mangrove band widths and minimum band widths required

District	**Location**	**Current Band Width, m**		**Minimum Band Width Required, m**
		Minimum	**Maximum**	
Kubang Pasu	Jerlun	55.5	966.5	802.5
	Kangkong	10.0	146.0	2105.2
Kota Setar	Kuala Kedah	13.5	267.0	422.8
Yan	Sungai Daun	16.0	103.5	587.4
Kuala Muda	Kuala Muda	24.0	97.0	910.8
	Merbok	37.5	213.0	602.9

Based on the table above, none of the locations has passed the minimum band width required for its current minimum band width. However, in some locations such as

Jerlun, the mangrove coverage was getting adequate as the band width increased. However, replantation is still needed so that the area with a lower mangrove band width than the required band width can give adequate security against the normal wave attack. A massive aquaculture activity was observed in the coastline of Jerlun and the current distribution might be due to the deforestation of mangroves to make way for this activity. Therefore, proper planning and management for mangrove rehabilitation should be established to strengthen the greenbelt. Besides, the maximum current band widths in some other locations including Kangkong, Kuala Kedah, Sungai Daun, Kuala Muda, and Merbok were not enough to fulfil the minimum band widths required, hence indicating these locations as prone to danger, and are subjected to high risk if higher wave height magnitudes hit the coastline.

Upon considering the worst-case scenario, the minimum current band width was set as the current band width; thus, comparing the current band width with the minimum required band width for acceptable protection has rather rendered every location vulnerable and in alarming conditions. Therefore, more mangroves should be replanted immediately along this endangered coastline to improve their protection capacities and eventually serve their ultimate function as a coastal barrier. Apart from being an economic solution, replantation is also an environmental-wise and nature-based option.

4.5.1 Replantation as a Mitigation Measure

In regions with normal wave conditions and densely wide mangrove forests, a slight band of mangrove may give a sufficient shelterbelt. Meanwhile, in an increasingly uncovered zone with visit storms and progressively open mangrove structures, more extensive bands are, hence, required. As such, by analyzing the current band width of mangroves at each location, replantation with a specific band width is suggested with the following guidance as expressed in Equation 4.1:

Required replantation band width (m) = Minimum required band width (m) – Current band width (m)

Equation 4.1

For instance, the minimum band width along the coastline in Jerlun is 55.5 m; hence, the determination of the required replantation can be done by subtracting 802.5 m (minimum required band width) with 55.5 m. This calculation was applied due to the non-uniformity of mangrove band width at one location along the shoreline. Apart from that, the selection of species is pivotal because different species recolonize differently in new or degraded habitat. *Rhizophora* is the most favorite for replantation [153] and was deemed ideal due to its fast growth, but it should rather be planted in monoculture [3]. Other factors including soil suitability and site selection should also be considered.

Besides, replantation of young seedlings might be hard since they have low survival rates due to the washing out of severe wave towards the shoreline; thus, nursery-raised seedlings might be an option. Engineering knowledge needs to be merged with forestry fundamental and strategy so that a successful replantation can be achieved. Conserving the current mangrove coverage as well as recovering the critically distributed degraded mangroves would also be the best actions to provide extra protection to this tidal habitat vegetation. This is vividly vital to maintain and conserve matured, dense, and great band width of mangrove trees, especially in areas where a great disaster once occurred.

4.5.2 Recommendation of Areas for Replantation

The river mouth of Kedah River, middle-southern region of Yan, southern region of Kuala Muda, as well as Sungai Melaka and Kuala Teriang, Langkawi may have the highest risk since communities are residing near the coastal areas. Even though no specific analysis was done in Langkawi sites, both sites are still very crucial considering the thin coverage yet narrow belt with the residential communities in the nearest coastal areas. Moreover, to make it worse, these sites were also affected during the 2004 IOT. The locations of these respective areas are presented in Figure 4.19 with A, B, C, and D representing Langkawi, the river mouth of Kedah River, the middle-southern region of Yan, and the Kuala Muda southern region, respectively.

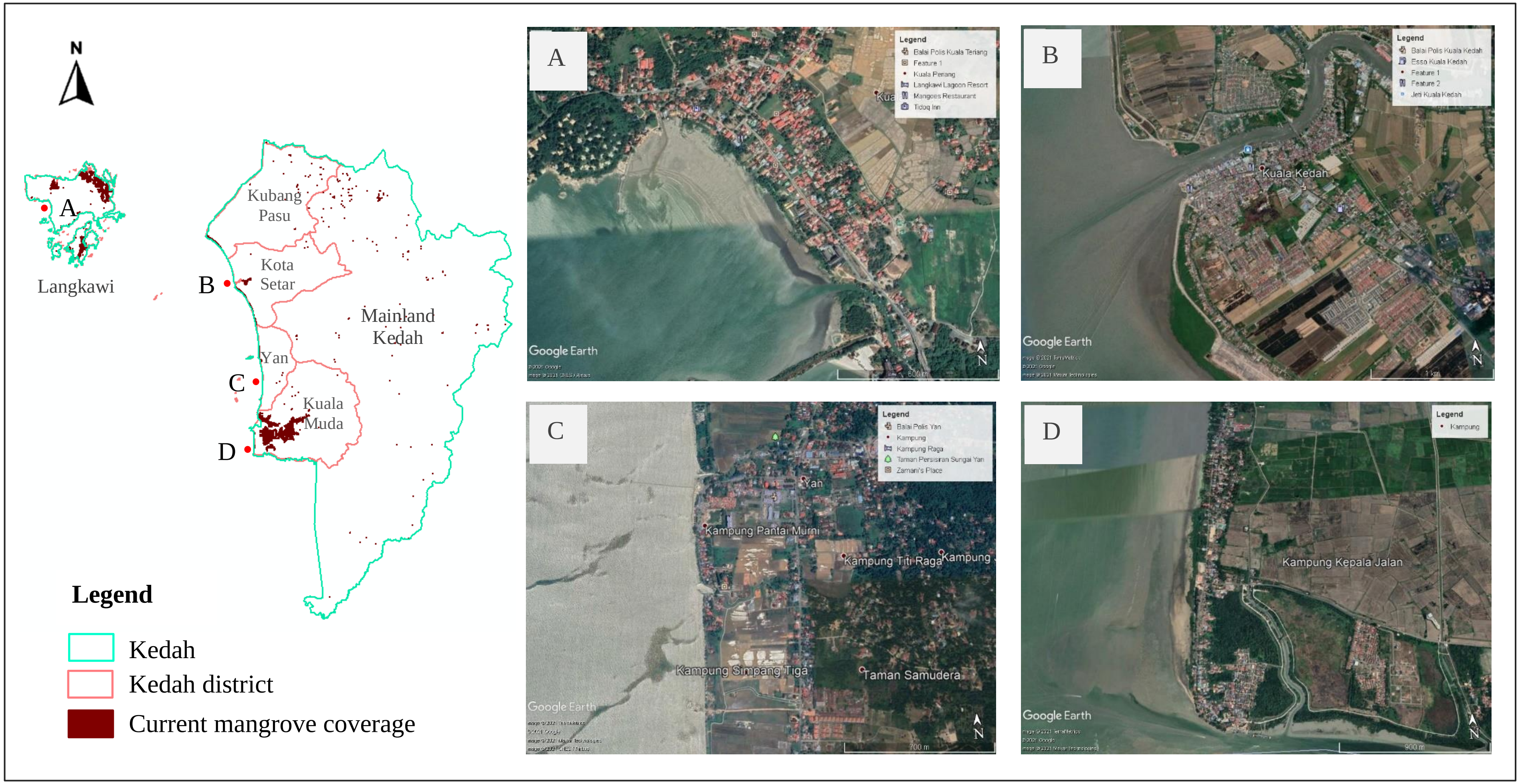


Figure 4.19: Locations of crucial areas

While the mangrove protection might not significantly differ in terms of band widths for other locations in the other districts, some considerations can be taken to make these areas less risky than the above-mentioned locations. For instance, earth dikes or bunds safeguarding the paddy fields from the direct intrusion of sea waves were built near the coastline. At the same time, this levee helps regulate the water level and control the seawater from entering the paddy field or inland besides acting as a barrier. These bunds are mostly found in the southern regions of Kubang Pasu, Kangkong, and Kuala Kedah.

Additionally, although revetment was observed near the middle-southern region of the Yan district, specifically at Kampung Pantai Murni, the residential area is, however, too close to the coastline. Hence, for a more promising safety level, this area would also be suggested for immediate replantation. Another consideration includes the agriculture and aquaculture activities near the coastline. Since paddy-farming is largely conducted in most of the inland areas along the coastal areas, the encroachment of aquaculture activities onto the mangrove forests as seen in the northern region of Kubang Pasu district and the southern region of Merbok, Kuala Muda may turn the respective areas to be less resided by large communities and, hence, less risky.

Thus, with these considerations, a recommendation for immediate replantation is mapped as depicted in Figure 4.20, but only in the crucial areas (refer to Figure 4.19). However, this does not imply that the other risky areas should receive less attention for quick actions, but immediate replantation in those areas are encouraged even more.

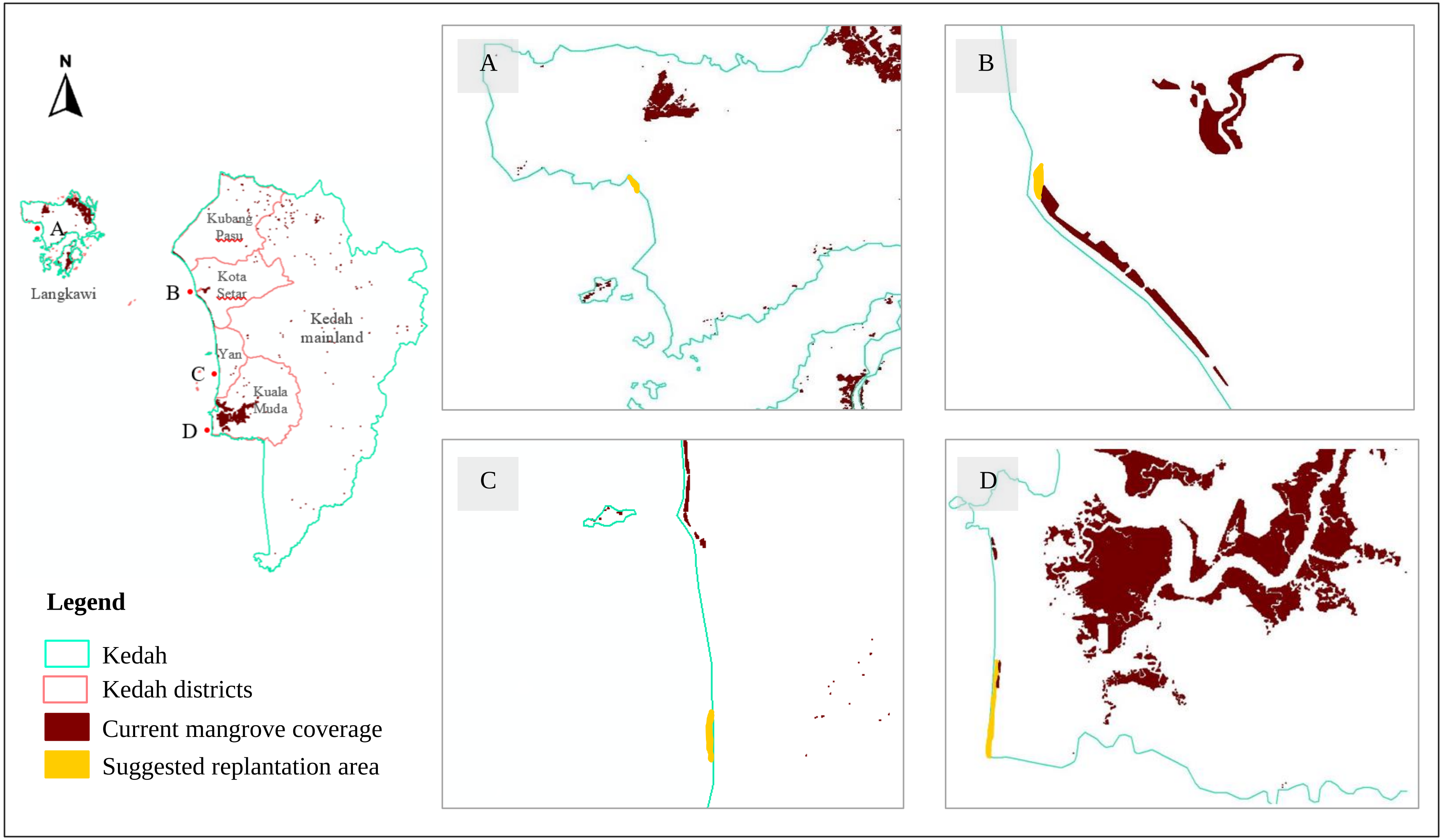


Figure 4.20: Suggested areas for mangrove replantation in Kedah

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Overview

Chapter 5 summarizes the overall study. Some recommendations are also provided in this chapter for future improvement or research.

5.2 Conclusion

The role of dense and healthy mangroves at the frontier has been recognized in dampening the amplitude of waves that struck coastlines. The submerged structures of mangrove that comprise roots, leaves, and trunks form rigid and stable mangrove trees that influence the hydrodynamic process once exposed to the incoming wave. Due to the interaction of both mangrove structures and wave actions, dissipation subsequently occurs. Thus, the main purpose of this study is to assess the sufficiency of mangrove coverage for protection services along the Kedah coastline.

Limited assessment on the adequacy of mangroves in shielding the coastal communities, especially along the west coast of Peninsular Malaysia with the history of being affected during the 2004 IOT has led to the development of the research objectives. The first objective has been achieved with the utilization of advanced satellite technologies of remote sensing and the Geographic Information System platform. 5,568.12 ha of mangroves were identified in five coastal districts of Kedah with sprawling mangroves to populate along rivers such as Merbok River, Kuala Kedah and Ayer Hangat, Langkawi than along the coastline. A loss of approximately 2,273.13 ha was also observed compared to 7,841.25 ha of mangroves found in 2012.

The second objective has discovered the wave heights before and after approaching the mangrove band. Incident wave height of 1.05 m, as the top wave height was recorded in Jerlun and Sungai Daun. In addition, the highest shoaling and refracted wave heights of 1.05 m and 0.92 m respectively were analyzed in both Jerlun and Sungai Daun too. While less transmission occurred in Kangkong with transmitted wave height of 0.68 m, Jerlun, however, recorded the greatest transmission with 0 m transmitted wave height.

The differences from both waves define the reduction performance of mangroves at each location. Waves were greatly attenuated in Jerlun, followed by Kuala Kedah, Merbok, Sungai Daun, and Kuala Muda. Jerlun demonstrated a 100% reduction performance from the initial incident wave height as it travelled through the maximum band width, while Kangkong showed the least dissipation rate of 33.6%, which can be associated with its low mangrove structures, density, and band width.

Information from the previous two objectives has enabled the determination of mangrove adequacy assessment. It was revealed that the coverage is rather low such that almost all locations are considered inadequate to provide optimum barrier towards the coastal area. Jerlun alone passes the required minimum band width for its current maximum band width and several villages along the Kuala Muda, Sungai Melaka, and Kuala Teriang coastline warrant for extra attention and immediate action for mangrove restoration for safety protection from disastrous hazards. Thus, to accomplish the most significant level of insurance from normal wind-induced wave, a minimum required mangrove band incorporating density with a high structure index is prescribed.

The replantation of mangroves in danger prone areas, especially the west coast of Malaysia is recommended where the location suits. Thus, regenerating mangroves along the uncovered coastline or deforested setting would be the best alternative to provide sufficient guard for the surrounding communities. Proper management along with constant monitoring could also enhance the process. Reduction in wave energy is accompanied by the reduction of shoreline erosion due to severe wave actions. This suggests that the restoration of degraded mangroves can be one step for erosion control.

5.3 Recommendations

There are some scopes presented in this study to be improved for future research, for instance, the utilization of Landsat 8 OLI in producing mangrove mapping. These medium-resolution satellite images may not be fine enough to distinguish individual objects compared to the high-resolution satellite images. Hence, this may affect the accuracy of the overall classification output. However, due to budget constraints, these images were opted by the researcher since they have an open-source and free data availability. Therefore, in future works, high-resolution images such as Quickbird or SPOT are recommended due to their finest resolution quality and better accuracy.

Some other suggestions include the production of numerical formula for wave attenuation determination but in a detailed categorization according to the species of mangroves. Bao's formula has it all by incorporating all influential factors in his formula; however, the limitation is that it may overgeneralize between the species of mangroves. Different species act differently with the hydrodynamics of waves as they possess different structure characteristics; therefore, a study on wave attenuation by considering all governing factors is suggested, but with different output and data representing the different species of mangroves.

Another recommendation would be to extend the assessment of mangrove adequacy by covering more areas on the west coast of Peninsular Malaysia such as Selangor and Pulau Pinang. This is because these states were also affected during the catastrophic Indian Ocean Tsunami in 2004 and, even worse, caused casualties in some parts of the states. Hence, future assessment to observe the recent status of mangroves is expected so that early protection measures can be taken, especially in danger prone areas and that well-managed forests can be achieved by proper administration.

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APPENDIX A

MANGROVE DATA OBTAINED DURING FIELD ASSESSMENT

H = Height, D = Diameter, W = Width, DBH = Diameter at breast height, N/A= data not available.

Date	Location	Species	Geometry (in m)						
			H. Tree	H. Canopy	H. Trunk	H. Root	W. Root	D. Trunk	DBH
15-Apr	Kampung Masjid, Kota Kuala Muda	*A. marina*	2.83	2.70	0.13	0.15	0.49	0.02	0.012
		A. marina	4.62	3.70	0.92	0.08	0.75	0.08	0.076
		A. marina	4.06	3.04	1.02	0.05	0.95	0.05	0.046
		A. marina	6.70	4.70	2.00	0.07	0.51	0.21	0.192
		A. marina	5.53	4.00	1.53	0.13	1.29	0.15	0.135
		A. marina	4.43	3.55	0.88	0.11	0.64	0.05	0.04
		A. marina	5.50	3.90	1.60	0.17	1.12	0.16	0.147
		A. marina	4.64	2.39	2.25	0.16	0.87	0.05	0.036
		A. marina	3.56	2.89	0.67	0.06	0.26	0.03	0.016
15-Apr	Kampung Tanjung Dawai, Merbok	*A. marina*	5.90	4.68	1.22	0.21	2.40	0.18	0.169
		A. marina	7.09	3.98	3.11	0.27	2.12	0.23	0.219
		A. marina	6.52	4.36	2.16	0.22	2.00	0.18	0.169
		A. marina	3.45	0.93	2.52	0.36	1.30	0.02	0.010
		A. marina	5.30	4.49	0.81	0.41	2.30	0.21	0.200
16-Apr	Kuala Teriang, Langkawi	*R. apiculata*	0.95	0.53	0.32	0.10	0.72	0.01	N/A
		A. marina	1.07	0.86	0.21	0.13	2.04	0.01	N/A
		A. marina	1.95	1.57	0.38	0.13	2.33	0.01	0.006
		A. marina	0.75	0.72	0.04	0.04	0.20	0.01	N/A
		A. marina	1.48	1.21	0.27	0.21	2.05	0.02	N/A
		A. marina	1.25	1.10	0.15	0.10	0.60	0.02	N/A
		A. marina	0.82	0.79	0.03	0.80	1.02	0.01	N/A
		A. marina	3.80	2.20	1.60	0.21	1.50	0.04	0.035
		A. marina	2.75	2.40	0.35	0.14	1.84	0.01	0.003
16-Apr	Sungai Melaka, Langkawi	*A. marina*	1.52	1.28	0.24	0.13	2.12	0.01	N/A
		A. marina	2.83	2.48	0.35	0.17	3.72	0.02	0.014
		A. marina	1.95	1.68	0.27	0.16	2.42	0.02	0.019
		A. marina	0.88	0.82	0.06	0.19	N/A	0.01	N/A
		A. marina	2.95	2.63	0.32	0.15	5.32	0.03	0.015
		A. marina	0.66	0.62	0.04	0.07	1.05	0.01	N/A
		A. marina	1.83	1.54	0.29	0.13	2.04	0.01	N/A
17-Apr	Kampung Baru Tepi Laut, Jerlun	*A. marina*	3.95	2.86	1.10	0.11	0.99	0.04	0.024
		A. marina	1.95	1.80	0.15	0.06	0.84	0.01	0.006
		R. mucronata	4.39	2.77	1.58	0.04	0.07	0.05	0.042
		A. marina	3.95	2.91	1.04	0.03	0.90	0.03	0.016
		A. marina	4.32	2.86	1.46	0.06	0.80	0.04	0.022

		A. marina	3.76	2.73	1.04	0.06	0.20	0.02	0.013
		A. marina	2.75	1.91	0.84	0.10	1.42	0.02	0.007
		A. marina	4.55	2.73	1.82	0.82	1.10	0.04	0.018
17-Apr	Kampung Tepi Laut, Kuala Kedah	*A. marina*	5.85	4.24	1.61	0.02	0.40	0.15	0.128
		A. marina	6.96	4.49	2.47	0.03	0.72	0.17	0.167
		A. marina	7.58	4.83	2.75	0.19	1.88	0.19	0.185
		A. marina	5.95	4.40	1.55	0.12	1.36	0.09	0.077
		A. marina	4.62	2.64	1.98	0.05	0.54	0.05	0.032
		A. alba	7.73	3.64	4.09	0.04	0.68	0.08	0.069
		A. officinalis	7.68	4.10	3.58	0.21	2.90	0.06	0.054
		A. alba	8.00	4.66	3.34	0.04	0.32	0.20	0.189
18-Apr	Kampung Permatang Sala Kechil, Kangkong	*A. marina*	3.00	2.18	0.82	0.14	2.87	0.02	0.011
		A. marina	2.15	1.80	0.35	0.23	2.40	0.02	0.005
		A. marina	1.06	0.91	0.15	0.04	0.12	0.01	N/A
		A. marina	2.73	2.56	0.17	0.14	0.49	0.02	0.013
		A. marina	2.92	2.14	0.78	0.08	0.62	0.03	0.024
		A. marina	2.98	2.38	0.60	0.11	2.50	0.03	0.012
		A. marina	3.24	2.50	0.74	0.07	0.59	0.02	N/A
		A. marina	3.15	2.63	0.52	0.18	3.20	0.03	0.014
18-Apr	Kampung Kuala Sungai Limau, Sungai Daun	*A. marina*	3.19	2.13	1.06	0.03	0.30	0.04	0.026
		A. officinalis	4.47	3.09	1.38	0.16	3.47	0.03	0.018
		A. marina	5.58	4.19	1.39	0.21	3.92	0.14	0.137
		A. marina	6.50	4.05	2.45	0.17	7.55	0.15	0.140
		A. marina	6.32	3.69	2.63	0.16	4.35	0.16	0.157
		A. marina	6.05	3.79	2.26	0.18	4.53	0.13	0.122

APPENDIX B

GROUND TRUTHING FOR GIS MAPPING

No.	Location	Feature	Coordinates	Ground Truth
1	Kuala Muda	Build-up	5°35'10.1"N 100°22'27.9"E	/
2		Agriculture	5°35'07.3"N 100°21'42.6"E	/
3		Mangrove	5°34'59.5"N 100°20'34.1"E	X (Forest)
4		Mangrove	5°38'40.6"N 100°20'25.2"E	/
5		Aquaculture	5°38'48.3"N 100°21'28.9"E	/
6		Mangrove	5°38'28.5"N 100°21'27.4"E	/
7	Merbok	Mangrove (Jetty)	5°40'50.0"N 100°23'07.0"E	/
8		Agriculture	5°41'21.1"N 100°23'01.7"E	/
9		Aquaculture	5°41'55.3"N 100°23'08.8"E	/
10		Build-up	5°41'14.5"N 100°22'03.9"E	/
11		Mangrove	5°41'24.9"N 100°21'21.6"E	/
12		Forest	5°44'58.6"N 100°21'41.5"E	/
13	Sungai Daun	Build-up	5°45'56.6"N 100°22'09.0"E	/
14		Aquaculture	5°49'25.9"N 100°22'14.2"E	/
15		Agriculture	5°49'22.6"N 100°22'13.1"E	/
16		Mangrove	5°52'02.4"N 100°21'42.4"E	/
17		Build-up	5°53'57.2"N 100°22'39.9"E	/
18		Agriculture	5°55'15.2"N 100°22'19.6"E	/
19	Kangkong	Build-up	6°00'13.0"N 100°20'38.1"E	/
20		Mangrove	6°00'11.6"N 100°20'31.7"E	/
21		Aquaculture	6°01'34.7"N 100°20'07.4"E	X (Build-up)
22		Mangrove	6°02'14.6"N 100°19'47.2"E	X (Forest)
23		Mangrove	6°02'32.2"N 100°19'40.9"E	/
24		Agriculture	6°02'19.1"N 100°20'09.3"E	/
25	Kuala Kedah	Build-up	6°05'14.4"N 100°18'42.9"E	/
26		Agriculture	6°05'24.2"N 100°18'37.6"E	/
27		Mangrove	6°05'42.3"N 100°17'05.4"E	/
28		Mangrove	6°04'53.6"N 100°17'57.3"E	/
29		Build-up	6°06'14.9"N 100°17'11.4"E	/
30		Agriculture	6°09'56.2"N 100°18'32.8"E	/
31	Jerlun	Mangrove	6°10'31.1"N 100°15'46.7"E	X (Forest)
32		Agriculture	6°13'38.2"N 100°15'03.7"E	/
33		Build-up	6°14'10.4"N 100°14'56.7"E	/
34		Agriculture	6°14'01.4"N 100°14'43.4"E	/
35		Aquaculture	6°13'43.5"N 100°14'25.9"E	/
36		Mangrove	6°13'15.2"N 100°13'59.8"E	/
37		Build-up	6°14'46.7"N 100°14'24.9"E	/
38	Langkawi	Build-up	6°19'36.2"N 99°50'29.2"E	/
39		Forest	6°21'02.5"N 99°52'13.3"E	/
40		Agriculture	6°25'34.8"N 99°48'17.0"E	/
41		Mangrove	6°26'19.4"N 99°48'19.3"E	/
42		Build-up	6°25'48.2"N 99°48'05.9"E	/
43		Mangrove	6°21'16.7"N 99°43'03.4"E	/

APPENDIX C

WAVE TRANSFORMATION ANALYSIS

District	Location	H_O, m	T, s	gT^2	L_O, m	d, m	d/L_O	d/L	L, m	K_S	H_S, m	K_R	$K_S.K_R$	H_R, m
Langkawi	Kuala Teriang	0.99	5.46	292.5	46.5	2.40	0.0516	0.0958	25.05	1.0172	1.01	0.8427	0.8572	0.85
	Sungai Melaka	0.99	5.46	292.5	46.5	2.40	0.0516	0.0958	25.05	1.0172	1.01	0.8427	0.8572	0.85
Kubang Pasu	Jerlun	0.99	5.46	292.5	46.5	1.90	0.0408	0.0842	22.57	1.0600	1.05	0.8747	0.9272	0.92
Kota Setar	Kangkong	0.99	5.46	292.5	46.5	2.20	0.0473	0.0913	24.10	1.0328	1.02	0.8553	0.8834	0.87
	Kuala Kedah	0.99	5.46	292.5	46.5	2.20	0.0473	0.0913	24.10	1.0328	1.02	0.8553	0.8834	0.87
Yan	Sungai Daun	0.99	5.46	292.5	46.5	1.90	0.0408	0.0842	22.57	1.0600	1.05	0.8747	0.9272	0.92
Kuala Muda	Kuala Muda	0.99	5.46	292.5	46.5	2.10	0.0451	0.0889	23.62	1.0416	1.03	0.8618	0.8977	0.89
	Merbok	0.99	5.46	292.5	46.5	2.60	0.0559	0.1002	25.95	1.0043	0.99	0.8300	0.8336	0.83

APPENDIX D

HEIGHT OF TRANSMITTED WAVE

A. Transmitted wave height over different band width

	Minimum transmitted wave, m	→								Maximum transmitted wave, m
					Jerlun					
(Band width, m)	55.5	156.7	257.9	359.2	460.4	561.6	662.8	764.1	865.3	966.5
e^(b*Bw)	0.6672	0.3190	0.1525	0.0729	0.0349	0.0167	0.0080	0.0038	0.0018	0.0009
	0.70	0.33	0.16	0.08	0.04	0.02	0.01	0.00	0.00	0.00
					Kangkong					
(Band width, m)	10.0	25.1	40.2	55.3	70.4	85.6	100.7	115.8	130.9	146.0
e^(b*Bw)	0.9727	0.9329	0.8947	0.8580	0.8229	0.7892	0.7569	0.7259	0.6962	0.6677
	0.99	0.95	0.91	0.87	0.84	0.80	0.77	0.74	0.71	0.68
					Kuala Kedah					
(Band width, m)	13.5	41.7	69.8	98.0	126.2	154.3	182.5	210.7	238.8	267.0
e^(b*Bw)	0.8303	0.5632	0.3821	0.2592	0.1758	0.1193	0.0809	0.0549	0.0372	0.0253
	0.84	0.57	0.39	0.26	0.18	0.12	0.08	0.06	0.04	0.03
					Sungai Daun					
(Band width, m)	16.0	25.7	35.4	45.2	54.9	64.6	74.3	84.1	93.8	103.5
e^(b*Bw)	0.8527	0.7740	0.7026	0.6377	0.5789	0.5255	0.4770	0.4329	0.3930	0.3567
	0.89	0.81	0.73	0.66	0.60	0.55	0.50	0.45	0.41	0.37
					Kuala Muda					
(Band width, m)	24.0	32.1	40.2	48.3	56.4	64.6	72.7	80.8	88.9	97.0
e^(b*Bw)	0.8575	0.8141	0.7729	0.7338	0.6966	0.6614	0.6279	0.5961	0.5659	0.5373
	0.88	0.83	0.79	0.75	0.71	0.68	0.64	0.61	0.58	0.55

	Minimum transmitted wave, m	→								**Maximum transmitted wave, m**
	Merbok									
(Band width, m)	37.5	57.0	76.5	96.0	115.5	135.0	154.5	174.0	193.5	213.0
e^(b*Bw)	0.6973	0.5781	0.4792	0.3973	0.3294	0.2731	0.2264	0.1877	0.1556	0.1290
	0.69	0.57	0.47	0.39	0.33	0.27	0.22	0.19	0.15	0.13

B. Transmitted wave height over similar range of band width

	Transmitted wave height, m				
Band Width, m	**55.5**	**65.9**	**76.3**	**86.6**	**97.0**
			Jerlun		
e^(b*Bw)	0.667224787	0.618617427	0.573551115	0.531767886	0.493028567
	0.70	0.64	0.60	0.55	0.51
			Kangkong		
e^(b*Bw)	0.857652761	0.83338359	0.809801168	0.786886062	0.76461939
	0.87	0.85	0.82	0.80	0.78
			Kuala Kedah		
e^(b*Bw)	0.465497892	0.403496037	0.349752502	0.30316732	0.262787038
	0.47	0.41	0.36	0.31	0.27
			Sungai Daun		
e^(b*Bw)	0.575365795	0.51888213	0.467943467	0.422005453	0.380577174
	0.60	0.54	0.49	0.44	0.40
			Kuala Muda		
e^(b*Bw)	0.700864619	0.655809124	0.613650048	0.574201194	0.537288332
	0.72	0.67	0.63	0.59	0.55
			Merbok		
e^(b*Bw)	0.586473525	0.530793357	0.4803995	0.434790068	0.393510824
	0.58	0.52	0.47	0.43	0.39

APPENDIX E

WAVE DISSIPATION, RATE OF ATTENUATION AND TRANSMISSION COEFFICIENT

A. Wave Dissipation, Attenuation Rate, and Transmission Coefficient over Different Band Width

Jerlun					
Band Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
55.5	1.05	0.70	0.35	33.8	0.66
156.7	1.05	0.33	0.72	68.3	0.32
257.9	1.05	0.16	0.89	84.9	0.15
359.2	1.05	0.08	0.97	92.8	0.07
460.4	1.05	0.04	1.01	96.5	0.03
561.6	1.05	0.02	1.03	98.3	0.02
662.8	1.05	0.01	1.04	99.2	0.01
764.1	1.05	0.00	1.05	100.0	0.00
865.3	1.05	0.00	1.05	100.0	0.00
966.5	1.05	0.00	1.05	100.0	0.00

Sungai Daun					
Band Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
16.0	1.05	0.89	0.16	15.4	0.85
25.7	1.05	0.81	0.24	23.2	0.77
35.4	1.05	0.73	0.32	30.3	0.70
45.2	1.05	0.66	0.39	36.7	0.63
54.9	1.05	0.60	0.45	42.5	0.57
64.6	1.05	0.55	0.50	47.8	0.52
74.3	1.05	0.50	0.55	52.7	0.47
84.1	1.05	0.45	0.60	57.0	0.43
93.8	1.05	0.41	0.64	61.0	0.39
103.5	1.05	0.37	0.68	64.6	0.35

Kangkong					
Band Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
10.0	1.02	0.99	0.03	3.1	0.97
25.1	1.02	0.95	0.07	7.1	0.93
40.2	1.02	0.91	0.11	10.9	0.89
55.3	1.02	0.87	0.15	14.6	0.85
70.4	1.02	0.84	0.18	18.1	0.82
85.6	1.02	0.80	0.22	21.4	0.79
100.7	1.02	0.77	0.25	24.6	0.75
115.8	1.02	0.74	0.28	27.7	0.72
130.9	1.02	0.71	0.31	30.7	0.69
146.0	1.02	0.68	0.34	33.5	0.66

Kuala Kedah					
Band Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
13.5	1.02	0.84	0.18	17.3	0.83
41.7	1.02	0.57	0.45	43.9	0.56
69.8	1.02	0.39	0.63	62.0	0.38
98.0	1.02	0.26	0.76	74.2	0.26
126.2	1.02	0.18	0.84	82.5	0.18
154.3	1.02	0.12	0.90	88.1	0.12
182.5	1.02	0.08	0.94	91.9	0.08
210.7	1.02	0.06	0.96	94.5	0.05
238.8	1.02	0.04	0.98	96.3	0.04
267.0	1.02	0.03	0.99	97.5	0.03

Merbok					
Band Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
37.5	0.99	0.69	0.30	30.4	0.70
57.0	0.99	0.57	0.42	42.3	0.58
76.5	0.99	0.47	0.52	52.2	0.48
96.0	0.99	0.39	0.60	60.4	0.40
115.5	0.99	0.33	0.66	67.1	0.33
135.0	0.99	0.27	0.72	72.8	0.27
154.5	0.99	0.22	0.77	77.4	0.23
174.0	0.99	0.19	0.80	81.3	0.19
193.5	0.99	0.15	0.84	84.5	0.16
213.0	0.99	0.13	0.86	87.1	0.13

Kuala Muda					
Band Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
24.0	1.03	0.88	0.15	14.7	0.85
32.1	1.03	0.83	0.20	19.0	0.81
40.2	1.03	0.79	0.24	23.1	0.77
48.3	1.03	0.75	0.28	27.0	0.73
56.4	1.03	0.71	0.32	30.7	0.69
64.6	1.03	0.68	0.35	34.2	0.66
72.7	1.03	0.64	0.39	37.6	0.62
80.8	1.03	0.61	0.42	40.7	0.59
88.9	1.03	0.58	0.45	43.7	0.56
97.0	1.03	0.55	0.48	46.6	0.53

B. Wave Dissipation, Attenuation Rate, and Transmission Coefficient over Similar Range of Band Width

Jerlun					
Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
55.5	1.05	0.70	0.35	33.8	0.66
65.9	1.05	0.64	0.41	38.6	0.61
76.3	1.05	0.60	0.45	43.1	0.57
86.6	1.05	0.55	0.50	47.2	0.53
97.0	1.05	0.51	0.54	51.1	0.49

Sg Daun					
Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
55.5	1.05	0.60	0.45	42.9	0.57
65.9	1.05	0.54	0.51	48.5	0.52
76.3	1.05	0.49	0.56	53.5	0.46
86.6	1.05	0.44	0.61	58.1	0.42
97.0	1.05	0.40	0.65	62.2	0.38

Kangkong					
Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
55.5	1.02	0.87	0.15	14.6	0.85
65.9	1.02	0.85	0.17	17.0	0.83
76.3	1.02	0.82	0.20	19.4	0.81
86.6	1.02	0.80	0.22	21.6	0.78
97.0	1.02	0.78	0.24	23.9	0.76

Kuala Kedah					
Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
55.5	1.02	0.47	0.55	53.6	0.46
65.9	1.02	0.41	0.61	59.8	0.40
76.3	1.02	0.36	0.66	65.2	0.35
86.6	1.02	0.31	0.71	69.8	0.30
97.0	1.02	0.27	0.75	73.8	0.26

Merbok					
Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
55.5	0.99	0.58	0.41	41.5	0.59
65.9	0.99	0.52	0.47	47.0	0.53
76.3	0.99	0.47	0.52	52.1	0.48
86.6	0.99	0.43	0.56	56.6	0.43
97.0	0.99	0.39	0.60	60.7	0.39

Kuala Muda					
Width, m	**Incident Wave, m**	**Transmitted Wave, m**	**Attenuated Wave, m**	**Reduction Rate, %**	**Transmission Coefficient**
55.5	1.03	0.72	0.31	30.3	0.70
65.9	1.03	0.67	0.36	34.8	0.65
76.3	1.03	0.63	0.40	39.0	0.61
86.6	1.03	0.59	0.44	42.9	0.57
97.0	1.03	0.55	0.48	46.6	0.53