

FRIM Special Publication No. 60

STATUS OF **MANGROVES** IN MALAYSIA

Hamdan Omar





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FOREST RESEARCH INSTITUTE MALAYSIA

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Foreword



The tsunami which hit Malaysia on 26 December 2004 resulted in the government among other things committing itself to enhancing the conservation efforts of mangroves areas. Recognising the destruction caused by the tsunami to life and property caused by the tsunami, it is timely that the government enhance coastal conservation efforts. Hence, the 4th National Biodiversity Council (MBBN) on January 13, 2005 decided that all state governments and Ministry of Natural Resources and Environment (NRE) to take initiative to restore and conserve ecosystems and vegetation of the mangrove forests.

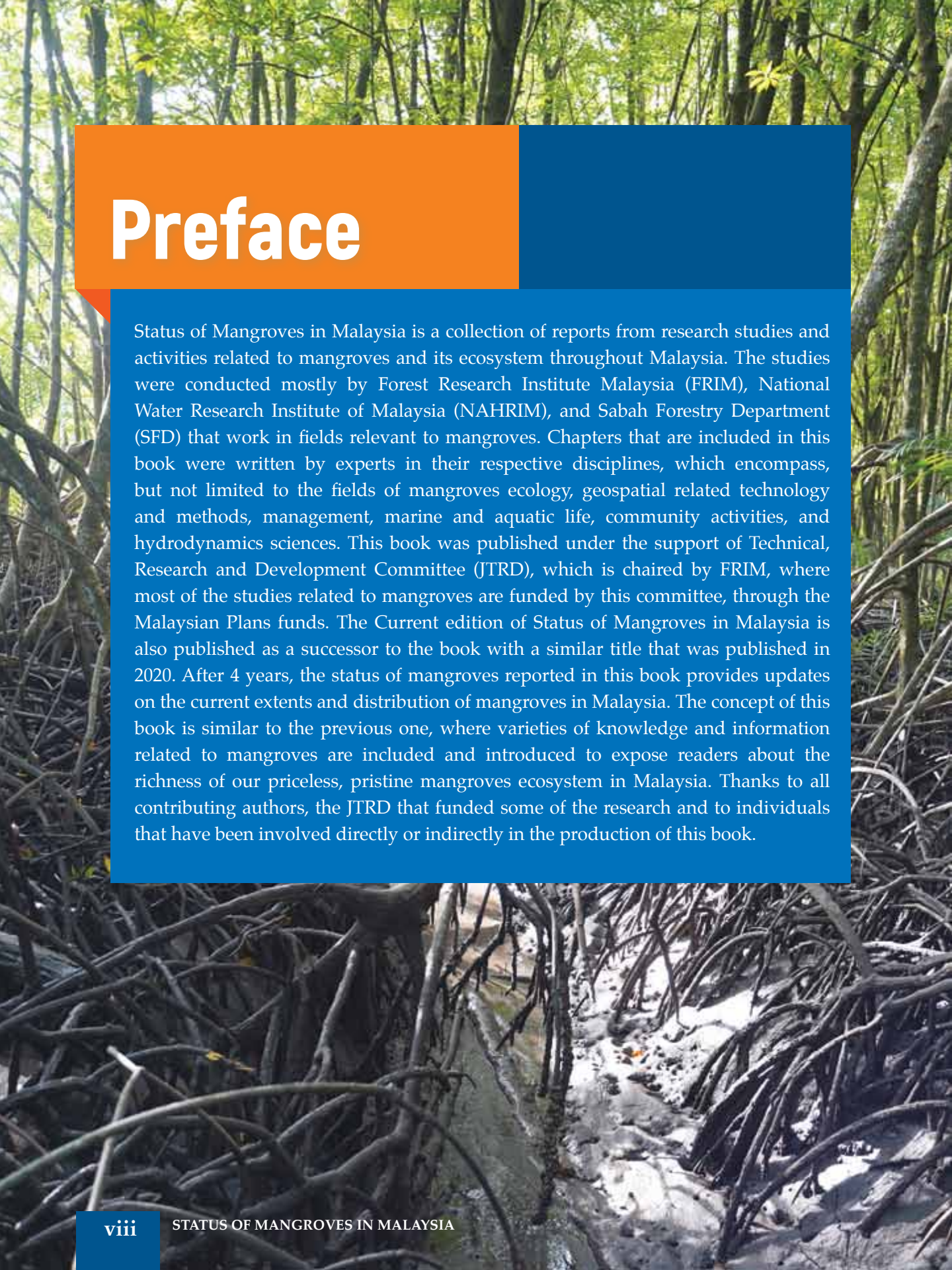
Under the Special Task Force chaired by Secretary General of NRE, now known as Ministry of Natural Resources and Environmental Sustainability (NRES), Director General of Forest Research Institute Malaysia (FRIM) has entrusted to chair of Research and Development Committee (JTRD) to carry out related research and development (R&D) activities. The main objective of JTRD in this regard is to support the implementation of rehabilitation programmes and to strengthen conservation efforts in the mangroves and coastal areas throughout the country .

The JTRD to date has organised seven seminars as platforms to present research findings not only from FRIM but also other agencies, institutions and universities related to forestry R&D. The committee has also produced various types of technical and semi-technical information, guidelines and publications including more than 30 books for reference purposes among relevant stakeholders.

We always encourage and support exchange of knowledge through seminars, publications and other ways of communication. Therefore, publication of this book is welcomed by the JTRD to further enhance our knowledge on scientific information related to mangroves. I believe that the readers will find this book enlightening and useful especially in generating for greater understanding of mangroves in Malaysia. It is also our hope that recommendations provided by authors of the various chapters can be adopted for management purposes of the mangroves which are priceless resources of our country.

DATO' DR. ISMAIL HJ. PARLAN

Director General, Forest Research Institute Malaysia (FRIM)
Chairman of Research and Development Committee (JTRD)

The background of the entire page is a photograph of a mangrove forest. The top half shows the dense green canopy of the trees, while the bottom half shows the intricate, dark, and tangled root systems of the mangroves growing out of the ground. The lighting is bright, suggesting a sunny day.

Preface

Status of Mangroves in Malaysia is a collection of reports from research studies and activities related to mangroves and its ecosystem throughout Malaysia. The studies were conducted mostly by Forest Research Institute Malaysia (FRIM), National Water Research Institute of Malaysia (NAHRIM), and Sabah Forestry Department (SFD) that work in fields relevant to mangroves. Chapters that are included in this book were written by experts in their respective disciplines, which encompass, but not limited to the fields of mangroves ecology, geospatial related technology and methods, management, marine and aquatic life, community activities, and hydrodynamics sciences. This book was published under the support of Technical, Research and Development Committee (JTRD), which is chaired by FRIM, where most of the studies related to mangroves are funded by this committee, through the Malaysian Plans funds. The Current edition of Status of Mangroves in Malaysia is also published as a successor to the book with a similar title that was published in 2020. After 4 years, the status of mangroves reported in this book provides updates on the current extents and distribution of mangroves in Malaysia. The concept of this book is similar to the previous one, where varieties of knowledge and information related to mangroves are included and introduced to expose readers about the richness of our priceless, pristine mangroves ecosystem in Malaysia. Thanks to all contributing authors, the JTRD that funded some of the research and to individuals that have been involved directly or indirectly in the production of this book.

A photograph of a person in a forest, wearing a dark shirt and a watch, using a measuring tape to measure the circumference of a large tree trunk. The forest is dense with green foliage and many trees. The person is positioned in the center-left of the frame, and the tree trunk they are measuring is on the right side of the frame. The background is filled with more trees and leaves, creating a lush green environment.

Chapter 9

A close-up photograph of mangrove roots, showing a complex network of thick, gnarled, and moss-covered roots extending from the ground. The roots are dark brown and have a rough, textured surface. The background is dark and out of focus, emphasizing the intricate structure of the roots.

Assessing the Impact of Stilt Root Systems on Coastal Protection: A Hydrodynamic Simulation Study

Assessing the Impact of Stilt Root Systems on Coastal Protection: A Hydrodynamic Simulation Study

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1. Introduction

Mangrove forests thrive in the upper intertidal zones of soft-sediment shores in tropical and subtropical regions [1]. This ecosystem is widely regarded as one of the most productive natural ecosystems globally and has well-established ecological, economic, and cultural characteristics [2]. It supports fisheries and biodiversity while also protecting coastlines from erosion and extreme weather events. These natural defences are highly desirable because they offer cost-effective solutions that deliver multiple benefits and contribute to both community and ecological resilience [3]. The unique design of this ecological system enables it to absorb hydrodynamic turbulence and maintain the function and structure of the ecosystem [4], attenuating the energy of tsunamis, cyclones, and storm surges while reducing the velocity of the channel floodplain [5].

Mangrove roots generate currents through jets, eddies, and turbulence, which dissipate the flow and energise the boundary layer separation, shear layer eddy mixing, and flow reattachment [6]. The decline in the drag coefficient for mangroves, which are considered to be the most rigid vegetation, was the most rapid as the Reynolds number increased. Wave dissipation in mangrove forests is caused by the frictional drag of dense trunks and induced roots [7] and is strongly influenced by the ratio of stem length to water depth, stem density, and forest density [8]. Additionally, forest characteristics such as stem and root diameter, forest floor slope, bathymetry, and wave characteristics [9] also play a significant role. The current velocity can fluctuate depending on the porosity, with less fluctuation behind a highly porous area [10]. These ecosystems can also create bed resistance by obstructing the flow of water through the forest [11] and may be more effective at protecting coastlines threatened by climate change than man-made structures [12].

The effectiveness of mangrove ecosystems in preventing soil loss and shoreline erosion has been well-documented [7]. By enhancing sediment deposition and promoting tree growth, these ecosystems can strengthen the anchorage of seedlings and stabilise the shoreline. For example, *Rhizophora mucronata* is commonly found in low-to mid-intertidal areas and invests more in root growth further down the intertidal gradient. Although many studies have focused on the attenuation of regular waves and the effect of wave characteristics on emerging and rigid vegetation [8], there is still a lack of datasets for model validation. Furthermore, most studies have not quantified the level of coastal defence in terms of service and information to coastal communities or the substrate and hydrological requirements for mangrove establishment [13, 14]. However, mangroves can play an important role in reducing the risk of coastal hazards, and the success of using mangroves for coastal defence is often hampered by a lack of reference to these requirements.

The scientific community has confirmed the role of mangroves in reducing sea-wave velocity. For instance, studies have shown that six-year-old mangrove forests that are 1.5 km wide can attenuate open sea wave heights from 1 meter to 0.05 meter [15]. Moreover, approximately 70% of the near-shore wave height can be reduced by mangroves [7]. Research indicates that mangroves are capable of absorbing 30-40% of the total force of a tsunami [16] and up to 90% with a stand density of 3000 trees per hectare [9]. The model estimates a 50% decline in wave energy by going 150 m into a *Rhizophora*-dominated forest at high tide and a 50% energy reduction within a 100-meter belt width of *Sonneratia* forests [1], which ranges the total dissipation from 200 m to 300 m. This finding is supported by [13], who observed a total reduction of 35% over the first 80 m of the forest, which estimates 228.5 meters for 100 an of energy dissipation. Fully grown mangrove forests can significantly attenuate the wave energy of a wind-generated surface by 20% per 100 m [12]. Another study found that mangrove forests can reduce wave height by approximately 20% over 100 m, and can reach up to 60% over a vegetation width of 300 m [17]. Both [12, 17] estimated a vegetation width of 500 m to allow total dissipation of wave energy. The above studies pointed to the vegetation width range for total dissipation of wave is 200 meters to 500 meters. These previous studies demonstrated that the minimum shoreline belt width required to enable coastal forests to function as natural shoreline protectors was 200 m.

This study also examined the potential protective role of mangroves in relation to wave dissipation [6] through an analysis of the root architecture of individual species and trees using Computational Fluid Dynamics (CFD) with Fluent analysis. The 2D and 3D numerical models were capable of simulating the fluid flow in an open channel. The assessment of mangrove protection and design is referred to as distributed drag, which is characterised by tree drag or bed friction coefficients. However, there is a lack of understanding on how tree drag coefficients vary with tree morphology, density, and arrangement, which is a significant source of uncertainty [1]. Numerical models of tree drag allow mangrove forest managers to effectively design mangrove restorations to maintain the natural protection function of coastal communities and assets [18].

Enhancing the management of mangrove areas may increase wave attenuation by determining the required forest bandwidth that considers wind and swell waves as well as a dense mangrove forest, including species with aerial roots [14]. Prior to this, a deeper analysis of the drag characteristics of the stilt-root model must be conducted to observe the disturbance created by the stilt-root model. A 3D stilt root model was developed to mimic shoreline species, and the reduction in drag value could be explained both vertically and horizontally by the velocity behaviour in response to mangrove trees [19]. Fluent analysis was conducted under specific flow conditions to investigate seawater flow through the stilt root model, which slows down the initial velocity. Velocity dissipation was measured from the velocity value extracted from the analysis path of the specimen.

In Malaysia, mangroves serve three primary purposes: pole and charcoal production, shoreline protection, and wave barriers to protect against severe storm events. However, their decline accelerates owing to both natural and human-induced pressures, which may decrease the effectiveness of the barrier function [20]. Therefore, forest managers must preserve and select appropriate species to create better wave barriers and contribute to coastal risk-reduction strategies [9, 13]. Knowledge of wave dissipation through coastal forests would enable forest managers to restore or plant mangroves in degraded and deforested settings to support the establishment of mangrove seedlings [14]. Additionally, artificial protection may be necessary to protect mangrove seedlings, especially at the edge of mangrove forests in areas with deeper channels and strong currents [21]. By lowering current velocities in the forest and decreasing erosion, these measures can help ensure the successful use of mangroves in coastal defence strategies. Involving coastal communities, planners, managers, and engineers in such initiatives is crucial [12]. Community-based approaches and mechanisms are essential to ensure the sustainable use of mangroves for shoreline protection and wave barrier functions [13].

2. Materials and Methods

2.1 Study site

The study site adopts the location of sensors installed by NAHRIM for wave attenuation analysis, at Lekir, Perak, Pulau Klang, and Selangor. However, due to limitation of field data, this study used data from the study plot at Lekir, Perak, to model the stilt root model, whereas velocity dissipation analysis based on density used data from the study plot at Pulau Klang, Selangor (**Figure 1**). A temporary plot measuring 10m × 10 m was established at Lekir, and data on tree species, DBH, location, and height were recorded. The aboveground architecture of stilt roots, including the diameter of tree trunks and roots, azimuth of roots, height of roots from the ground level, distance between trees, and spacing of plantings, was recorded for the analysis of drag coefficients. At Pulau Klang, three temporary plot sizes were established to measure the density of mangrove stands per hectare,

representing low (2125), average (3850), and high (5250) densities, located at GPS coordinates (3.06076, 101.30462), (3.05886, 101.30310), and (3.04792, 101.29761) respectively. The data collected from these plots will be used to further our understanding of the factors that influence the growth and survival of mangrove forests in these locations.

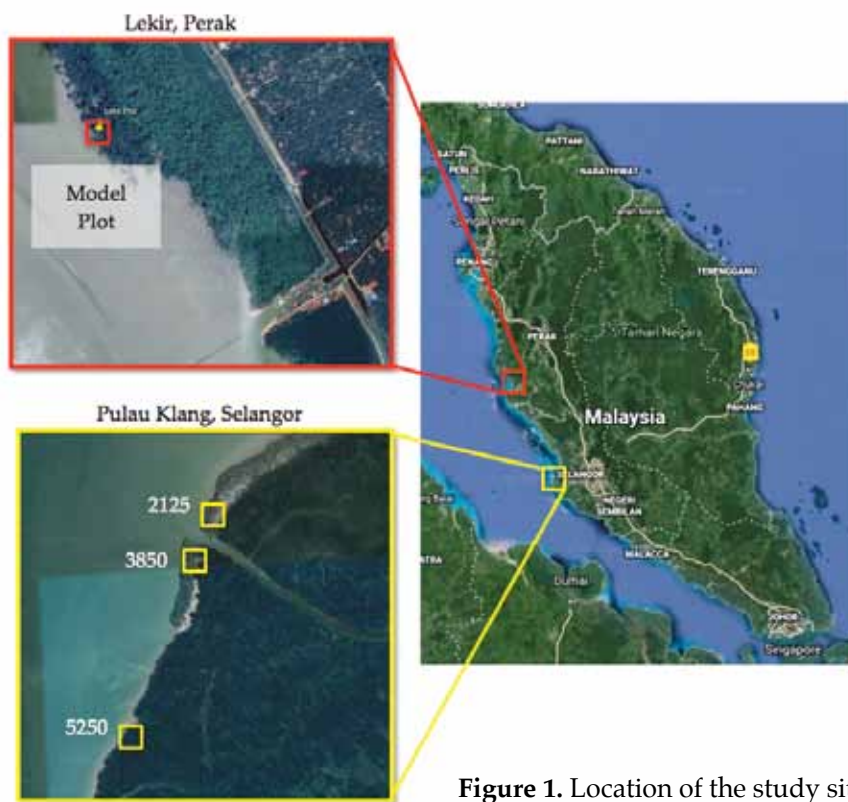


Figure 1. Location of the study sites.

2.2 Stilt Root Model

The model, located in Lekir, Perak, comprised 11 trees from two species, *Rhizophora apiculata* and *Sonneratia alba*, with ratios of 55% and 45% respectively. However, this study selected only four of these trees, which were successfully simulated to determine the drag value of the stilt root model and were capable of defining the velocity-dissipation trend. The selected stilt root models are listed in **Table 1** and consisted of two models for each species.

Table 1. Trees for stilt root model.

Model	Species	Local name	ID	DBH (cm)	Height (m)
1	<i>Sonneratia alba</i>	Perepat	3	47.3	22
2	<i>Rhizophora apiculata</i>	Bakau Minyak	4	23.7	18.5
3	<i>Sonneratia alba</i>	Perepat	6	33	18
4	<i>Rhizophora apiculata</i>	Bakau Minyak	8	18.5	15

The above-ground architecture of the stilt root model was modelled in 3D (**Figure 2**) using the SketchUp program, considering the diameter and orientation of each root. The analysis of the drag coefficient of these stilt root models focused on a plane surface parallel to seawater velocity. These plane surfaces were sliced vertically from the stilt root models at constant spacing, and these slices contained the root cross section as the main geometry input for the simulation.

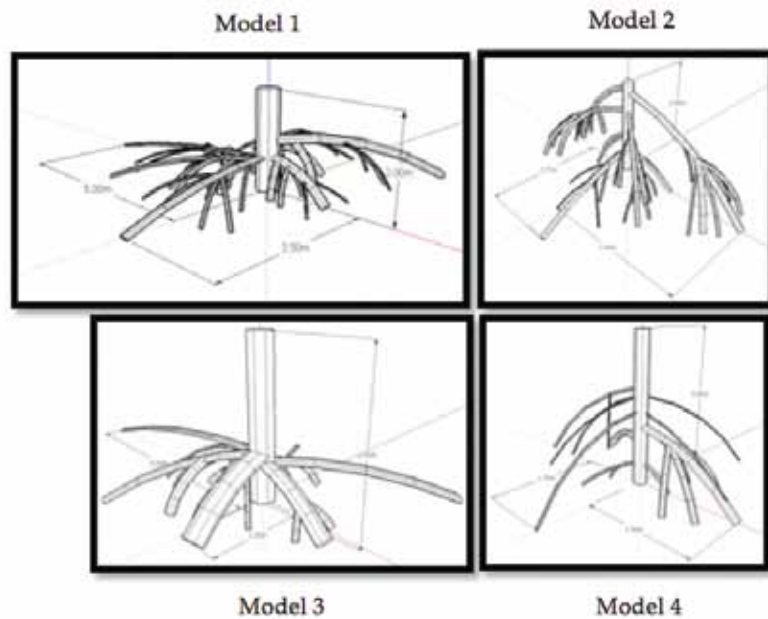


Figure 2. Stilt root models.

2.3 Computational Fluid Dynamics

The Computational Fluid Dynamics (CFD) software ANSYS Fluent was employed to conduct a thorough analysis and determine the drag coefficient of the above-ground stilt root system. The same approach was used to evaluate the dissipation behaviour of the seawater velocity along an in-line specimen. To ensure accuracy, simulations were conducted in two dimensions (2D) and vertical variation was considered to minimise hydrodynamic errors [22]. The first analysis calculated the drag value on the surface plane of the sliced cross sections, while the latter assessed the velocity dissipation for the shoreline belt width.

Two-dimensional specimens were meshed using a triangular method with an element size of 0.025 m. The density of seawater was 1023.387 kilograms per cubic meter, and the viscosity was 0.000959 kilograms per meter per second for both analyses. The Reynolds numbers for the mangrove root drag analysis and velocity reduction were 356,852 and 320,142, respectively, which classified both analyses as turbulent flow. Therefore, this study utilised a standard k-epsilon turbulent viscous model of the SIMPLEC solution type. The analysis was performed using a pressure-based approach, absolute velocity formulation, and steady time series.

Both analyses utilised the average water velocity at the inlet, which represents the average water velocity in the mangrove stands. The average magnitude of water velocity is approximately 0.1 m.s^{-1} [1]. This inlet velocity value was also employed by [5], who satisfied the Froude number similarity with the real field scale of tidal flow and storm surge, 0.2 m.s^{-1} and 0.5 m.s^{-1} . Hence, in this study, the researchers utilised 0.1 m.s^{-1} for the inlet velocity value in the drag analysis of the stilt root model and the velocity dissipation of the tree stand. The results generated from these simulations, in which the average velocity magnitude was applied to the inlet, were multiplied by the velocity ratio of the extreme velocity conditions, which was 0.5. The simulation was assumed to produce a significant reduction in the drag value of the flow redistribution in the horizontal plane with channel-average velocity [19].

2.4 Stilt Root Drag Value

The first step in the analysis was to determine the drag value of the stilt root model. A series of simulations were conducted in 3D but unfortunately resulted in errors. As a result, the analysis was simplified to a 2D model. The drag value is proportional to both the frontal area and the squared velocity. It is important to note that an increase in velocity in the lower frontal area results in overall drag reduction [19]. In this study, the drag coefficient of the stilt root model was analysed by creating horizontal slices of the model at intervals of 0.25 meters (as shown in **Figure 3**).

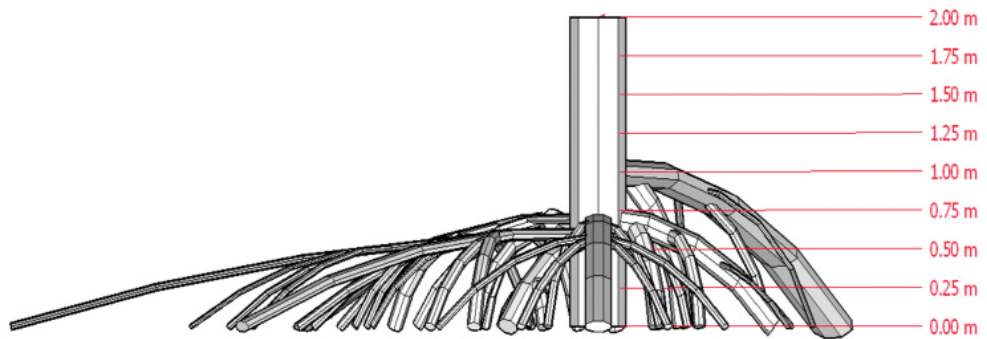


Figure 3. Vertical interval of specimen slices.

Based on **Figure 3**, six specimens were selected for the drag value analysis, which consisted of cross sections of mangrove stilt roots. Simulations for slices above 1.25 m and below 2.00 m were excluded owing to similar cross sections as slice 1.25 m. Therefore, this study focused on simulations with stilt root heights from 0 m to 1.25 m of stilt root height, as shown in **Figure 4**.

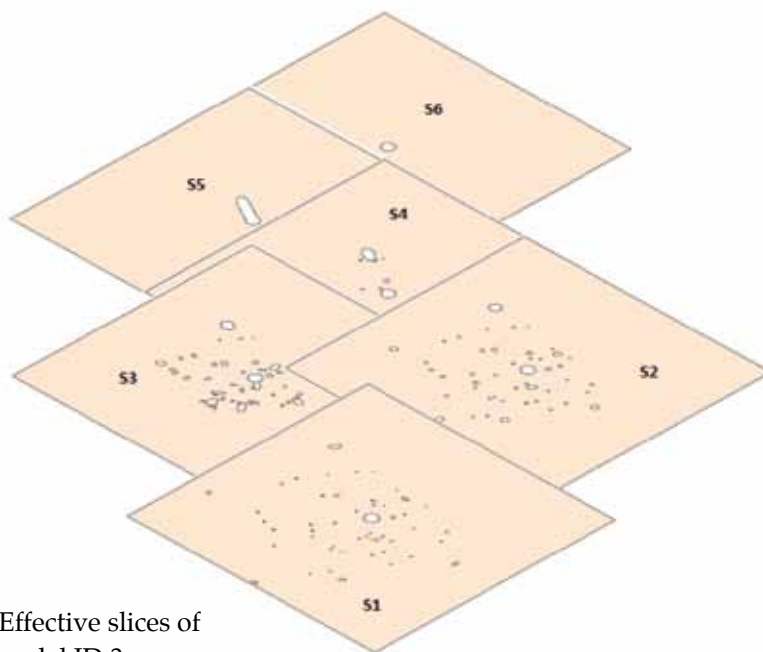


Figure 4. Effective slices of stilt root model ID 3.

The four stilt root models were successfully analysed for their drag values and velocity dissipation. A summary of the drag value results for the four models comprising 26 slices of the specimens is presented in **Table 2**. Additionally, images of the velocity contour, drag force, and drag value along the velocity flow in each slice were captured for further examination.

Table 2. Effective slices of stilt root model and range.

Stilt Root	No of Slices	Slice Range (m)	Root Height (m)
Model 1	6	0 - 1.25	1.07
Model 2	9	0 - 2.00	1.91
Model 3	4	0 - 0.75	0.66
Model 4	7	0 - 1.50	1.29

2.5 Velocity Dissipation

The aforementioned velocity dissipation analysis involved the utilisation of a specimen preparation technique that incorporated the slice that exhibited the highest drag value. This approach employs the height of the stilt root model at the aforementioned maximum drag value to prepare the specimen for analysis. The aforementioned analysis encompassed the preparation of specimens based on the three distinct tree stand densities. Specifically, these densities comprised 2125, 3850, and 5250 trees per hectare, which corresponded with low, average, and high stand densities respectively.

The velocity of the line distribution in the model was noticeably reduced compared with the average channel velocity. A slower velocity along the line near the trees would also decrease the force on the tree and alter the drag force over distance [19]. Consequently, in this study, the specimens were arranged with in-line distribution according to the specified density, with calculated tree gap spacing of 2.17 m, 1.61 m, and 1.37 m for specimens 2125, 3850, and 5250 respectively (**Figure 5**).

Figure 6 shows the boundary conditions assigned to the specimen prior to calculation. The analysis path was designated as the centre of the tree stem diameter following the inline distribution. The velocity magnitudes observed along the analysis path were recorded to analyse the velocity dissipation behavior of each stilt root model. The focus of the velocity dissipation analysis was on the path at the centre of the specimen, extending from the inlet to the outlet, within the fluid domain.

In this study, four specimens were analysed to examine the dissipation behaviour of an in-line tree stand with three densities. The cross-section of the sliced stilt root model on the specimen influenced the velocity that intersected the analysis path. Therefore, this study concluded that it is applicable only to a single path for analysis within the fluid domain. These specimens were prepared by crossing the stilt root model at the maximum drag value, which is the minimum shoreline belt width for a coastal forest stand. This width can be calculated using the equation generated from the trend line when the velocity is completely dissipated ($Y = 0$). The outer dimensions of the specimens varied owing to the different tree gap spacings.

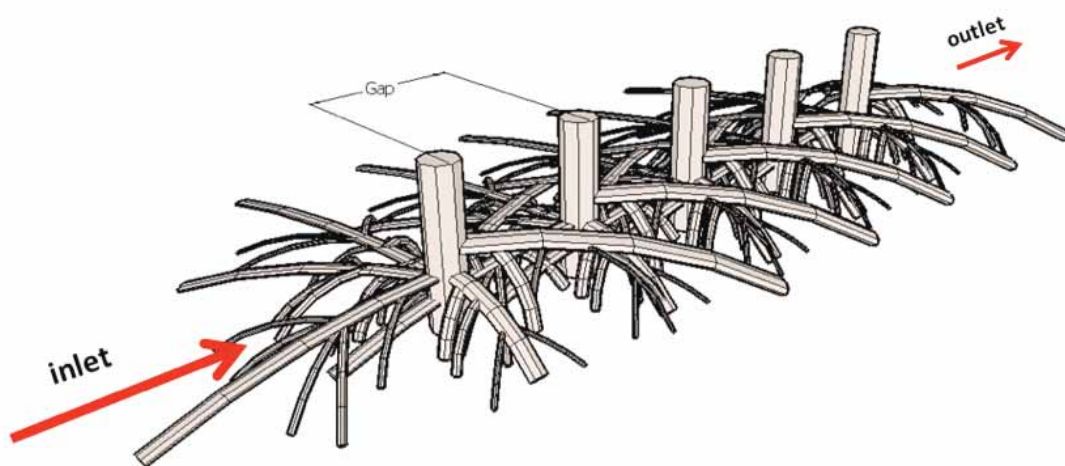


Figure 5. Stilt root models for velocity reduction in-line distribution.

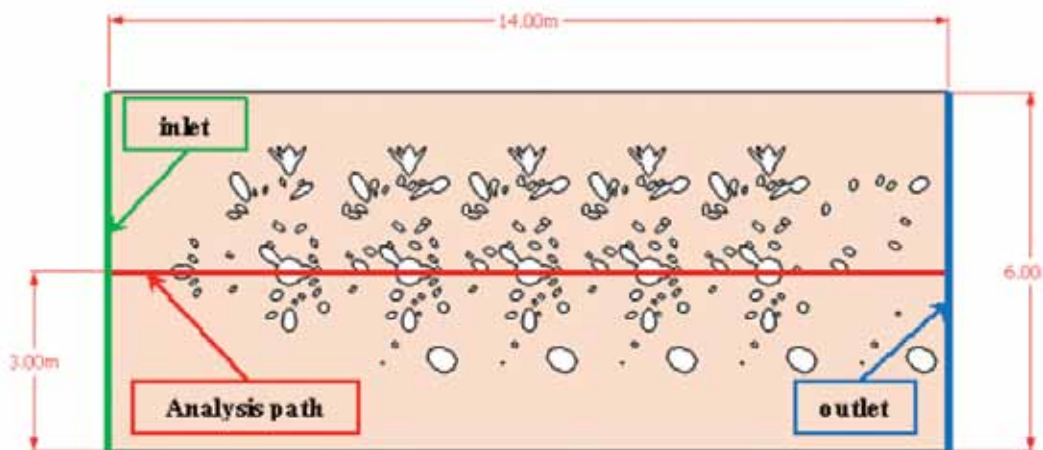


Figure 6. Specimen for velocity reduction in-line distribution.

3. Results

3.1 Stilt Root Drag Value

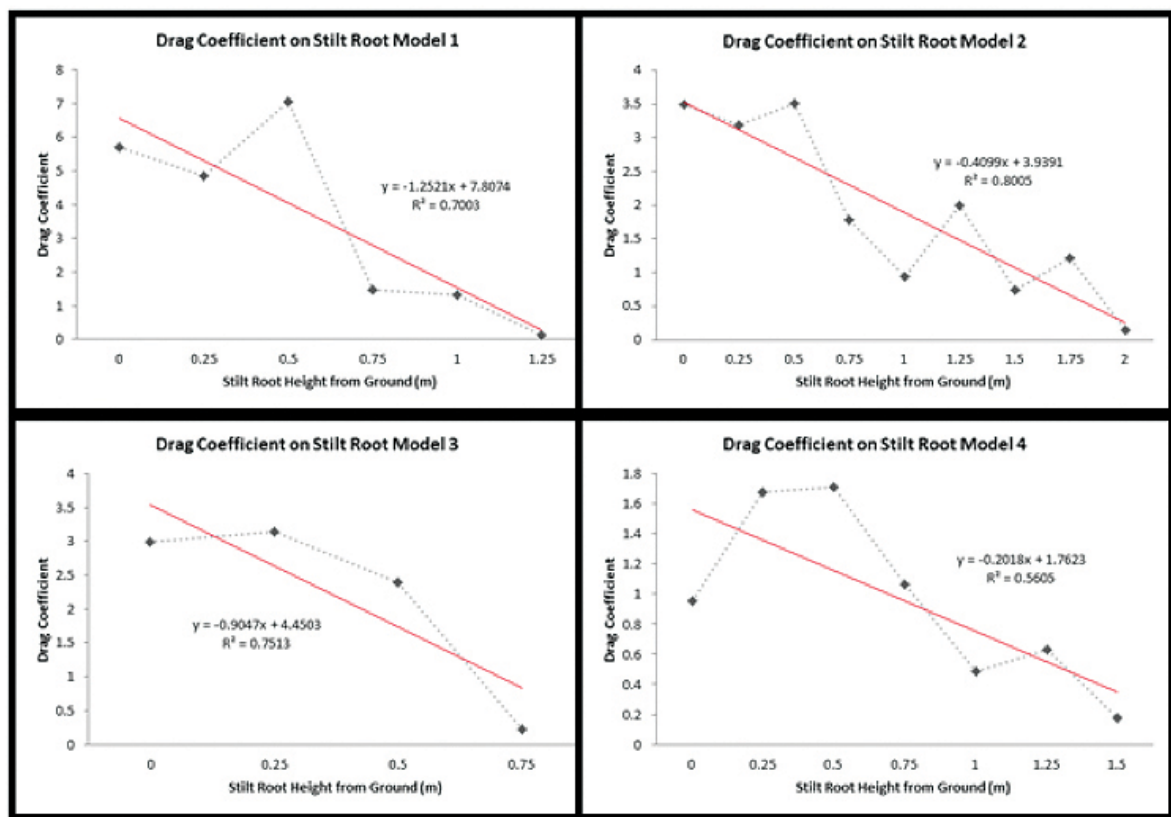


Figure 7. Drag coefficients for all stilt root models.

The results of the drag coefficient analysis of the specimens revealed that the maximum drag values were 7.0493, 3.5041, 3.1364, and 1.7067 for Models 1, 2, 3, and 4, respectively (**Figure 7**). Specifically, the height of slice for these values was 0.5 meters for Models 1, 2, and 4, while it was 0.25 meters for Model 3. The percentage ratio of the height of the maximum drag coefficient to the mangrove stilt root height from the ground level was 40% for Model 1, 25% for Model 2, and 33% for Models 3 and 4. The average total height of the four root models was 1.233 m. The results indicate that the average percentage ratio of the slice height at the maximum drag value was 32.75%, which was approximately 0.404 m from the ground level. The drag coefficient values decreased from the bottom to the top of the stilt root model.

When seawater flows through a forest, the velocity at which it passes through each mangrove tree is influenced by the drag. A higher drag value reduces the seawater velocity. The highest velocity was expected to occur in the uppermost vertical slices, which comprised only the cross section of the DBH for that particular tree. This finding aligns with those of [19], who observed that the velocity profile was almost uniform, except in the vicinity of the bed, where the velocity decreased in the root zone and was higher above the root zone.

Velocity Dissipation

The flow velocity in the in-line model was observed at three stand densities: 2125, 3850, and 5250. The trend line is extracted from the velocity values through the analysis path. From the simulation results of the velocity behaviour, it was observed that the trend line showed a decrease in velocity from the inlet at the first stilt root to the outlet at the last stilt root model in-line distribution, except for Model 3 at a density of 5250. This finding is similar to that of [6] who estimated a 40% decrease in the velocity magnitude of the initial flow. The results of the velocity behaviour for density 2125 for the four-stilt root model are shown in **Figure 8**, and the length of the tree distribution with a 2.17 m tree spacing gap that could totally dissipate the inlet velocity are summarised in **Table 3**.

Table 3. Total dissipation lengths for stilt root models 2125 density.

Root	Model 1	Model 2	Model 3	Model 4
Length	27.00	40.60	26.10	70.60

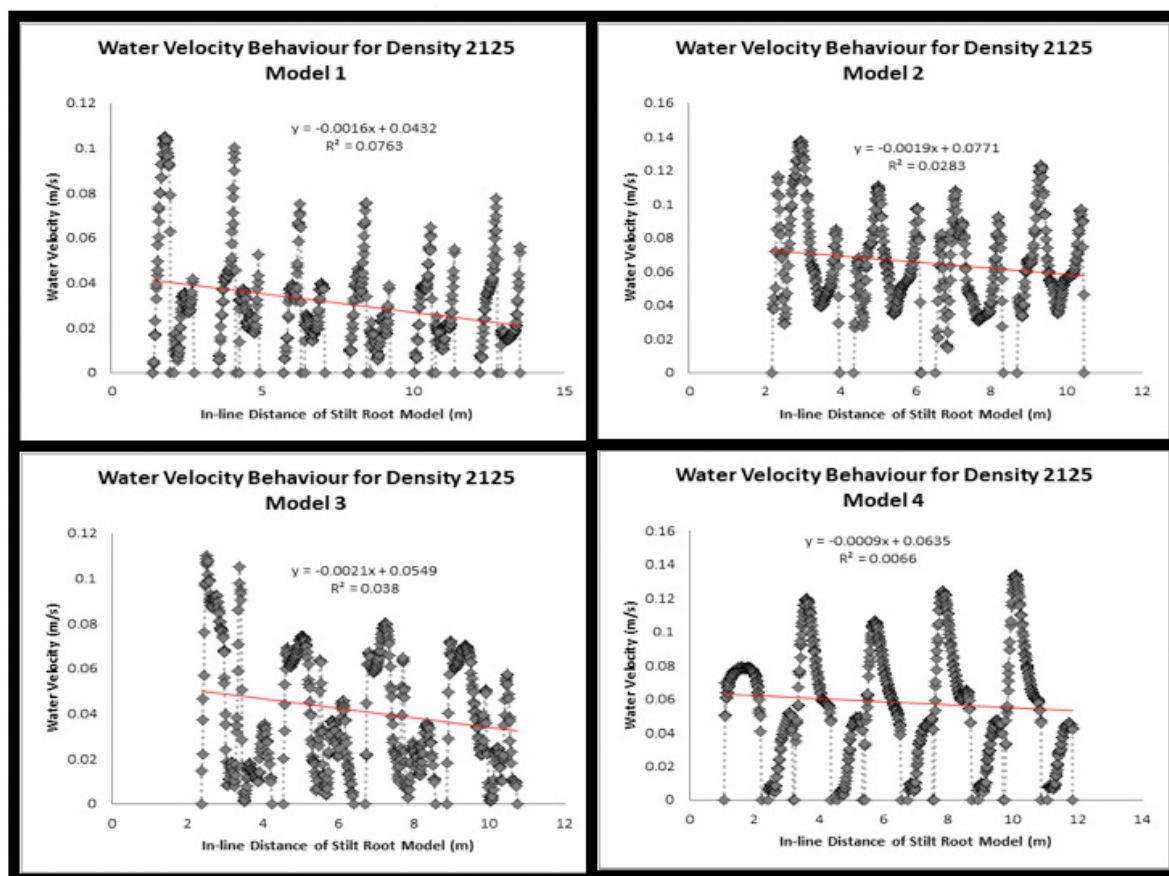


Figure 8. Velocity behaviour of stilt root models for density 2125.

The results of the velocity behaviour for a density of 3850 kg/m³ in the four-stilt root model are shown in **Figure 9**. Additionally, the findings on the length of the tree distribution capable of entirely dissipating the inlet velocity, with a 1.61 m tree spacing gap, are detailed in **Table 4**.

Table 4. Total dissipation lengths for stilt root models 3850 density.

Root	Model 1	Model 2	Model 3	Model 4
Length	26.30	31.40	17.30	315.00

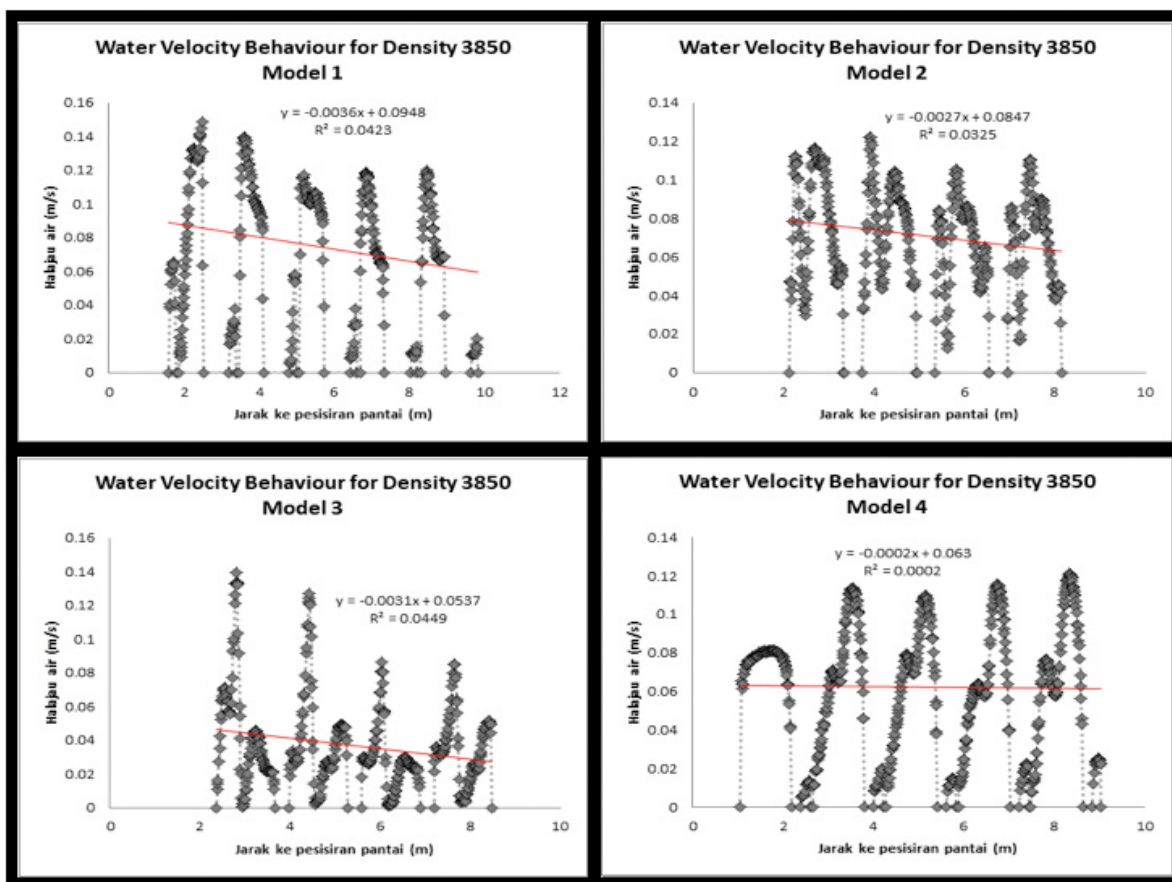


Figure 9. Velocity behaviour of stilt root models for density 3850.

The findings related to the velocity behaviour for a density of 5250 for the four stilt root models are presented in **Figure 10**, and the extent of the tree distribution with a 1.37 m tree spacing gap that can completely dissipate the inlet velocity is detailed in **Table 5**.

Table 5. Total dissipation lengths for stilt root models 5250 density.

Root	Model 1	Model 2	Model 3	Model 4
Length	23.70	18.20	-14.40	16.60

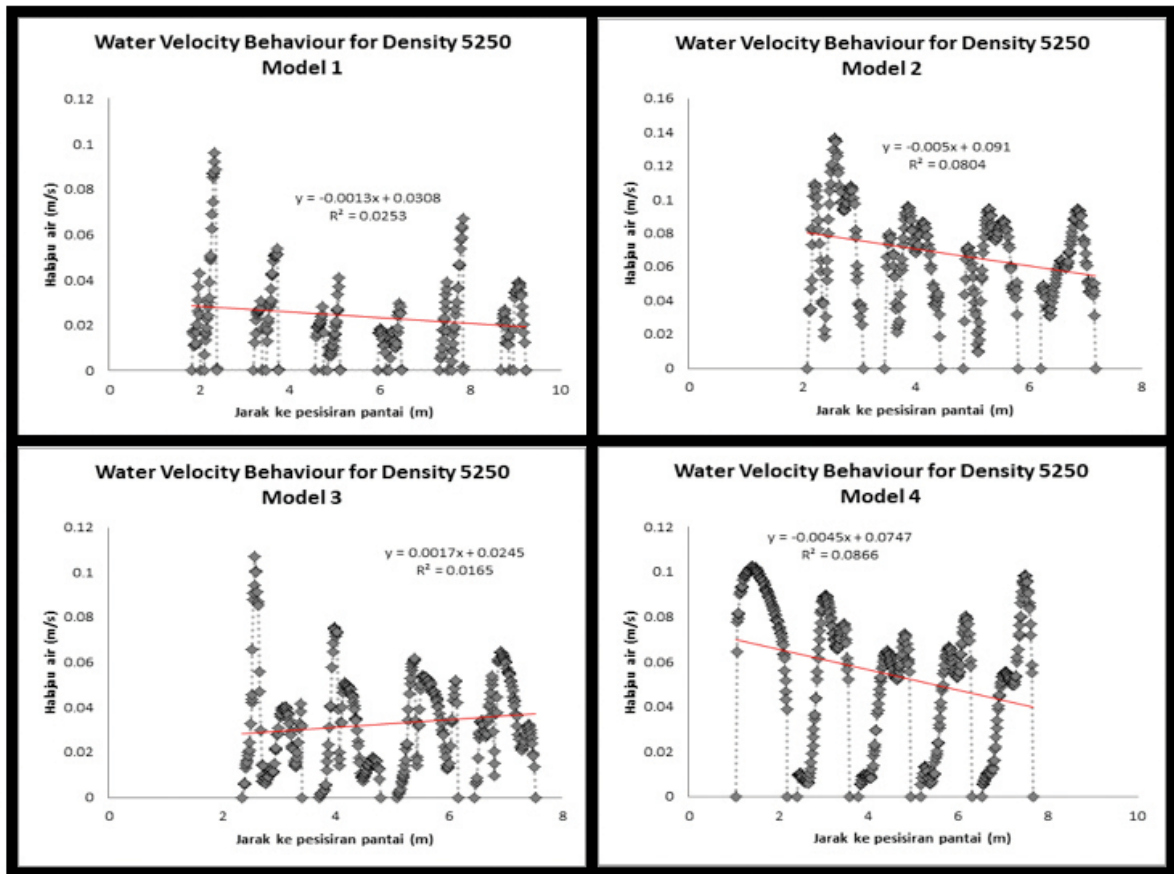


Figure 10. Velocity behaviour of stilt root models for density 5250.

The architecture of the stilt root model has a substantial impact on the velocity dissipation behaviour, which aligns with the findings of [6], who stated that root properties and coordination play a crucial role in reducing flow velocity owing to root densities and cross-sections. The research conducted by [6] supports the idea that the properties and coordination of roots significantly influence velocity dissipation behaviour.

4. Discussion

The analysis of drag distribution within the stilt root model revealed a progressive increment towards the ground level, indicating a notable deceleration of water flow velocity around the coastal stand within the stilt root system as opposed to the stem. This observation underpins the inference that drag values correlate positively and linearly with the cross-sectional area of the stilt root model and can be effectively approximated by employing the stem diameter at breast height (DBH). It was deduced that, for a stilt-rooted coastal tree, an increase in DBH is associated with a consequent elevation in drag values for a given tree stand.

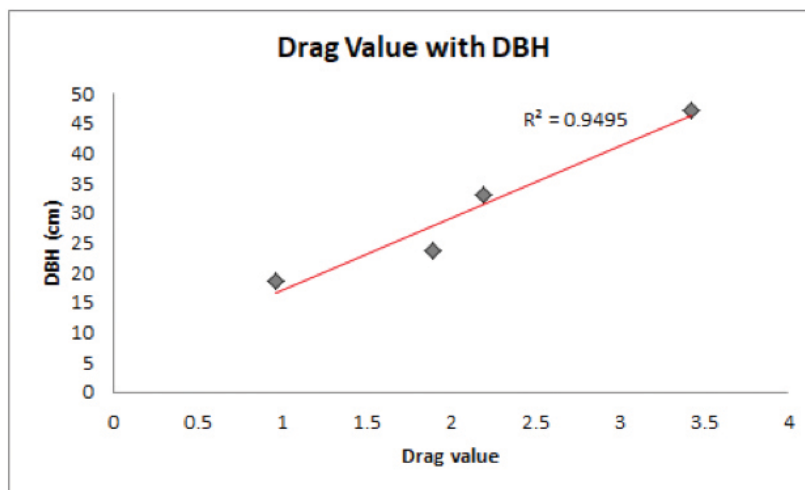


Figure 11. Relationship drag value and DBH.

The findings from the simulations executed with four distinct models, each with different densities, are shown in **Table 6**. Nonetheless, given the significant differences observed in the outcomes of Models 3 and 4, which exceeded the permissible limits, it was deemed necessary to eliminate them from subsequent evaluations.

Table 6. Summary of dissipation length.

Simulation Result Length				Modified Data Length		
Density	2125	3850	5250	2125	3850	5250
Model 1	27.00	26.30	23.70	27.00	26.30	23.70
Model 2	40.60	31.40	18.20	40.60	31.40	18.20
Model 3	26.10	17.30	-14.40	26.10	17.30	-
Model 4	70.60	315.00	16.60	70.60	-	16.60
Average				41.08	25.00	19.50

The refined results, deemed satisfactory, are compiled in **Table 7**, showing the average dissipation lengths across the four stilt root models for a density of 2125 and across three models for densities of 3850 and 5250, inclusive of planting spacing gaps. It is paramount to acknowledge that the velocity dissipation length serves as an indicator of the minimal shoreline width required for the attenuation of the seawater velocity.

Table 7. Average of shoreline width for all densities.

Stand Density	2125	3850	5250
Planting Spacing Gap	2.17	1.61	1.37
Shoreline Width	41.08	25.00	19.50

When plotting the averages of the shoreline belt widths against stand density, a linear correlation was established, as depicted in **Figure 12**. The derived equation $y = -0.007x + 54.702$ elucidates the relationship between the minimum shoreline belt width (Y-axis) necessary for the comprehensive dissipation of seawater velocity through mangrove trees and stand density (X-axis).

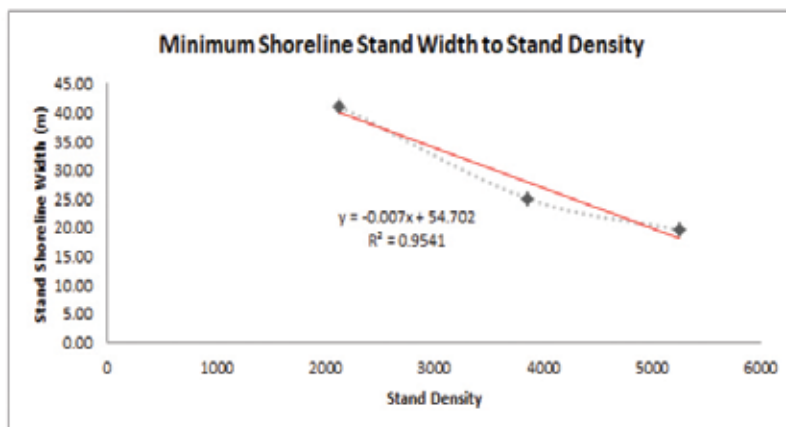


Figure 12. Average shoreline belt width with density.

Figure 13 shows the determination of spacing gaps for new plantations using a derived trend line and equation, $y = 27.277x - 18.3$, correlating with the minimum shoreline belt width (Y-axis) with the planting spacing gap (X-axis). The formulation for ascertaining the dissipation length, predicated on the velocity magnitude averages of 0.1 m.s^{-1} from four stilt root models, provides a foundational metric. In scenarios of heightened seawater velocity, 0.5 m.s^{-1} , the stipulated minimum shoreline belt width is deduced by amplifying the baseline width by the velocity ratio. Employing the lowest observed density of 2125, the calculated minimum shoreline belt width stood at 41.08 m, which, under extreme velocity conditions (velocity ratio of 5), escalates to 205.4 m. This delineation positions the coastal forest as a pivotal natural barrier against shoreline erosion, aligning with findings by [9, 14], who posited minimum shoreline belt widths of 200 m and 228.5 m respectively, to fully mitigate wave energy.

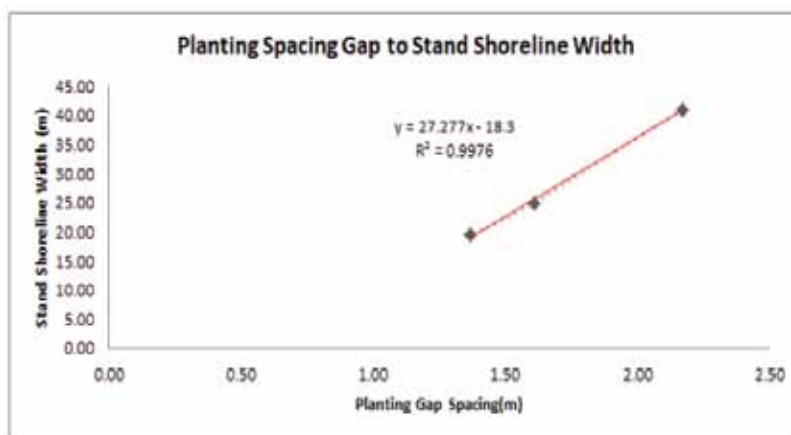


Figure 13. Average shoreline belt width with spacing gap.

5. Conclusion

Mangrove forests are highly productive ecosystems that provide multiple benefits such as fisheries, biodiversity, and coastline protection. These are cost-effective solutions that deliver multiple benefits and contribute to both community and ecological resilience. Wave dissipation in mangrove forests is due to the frictional drag of dense trunks and induced roots, and is strongly influenced by the ratio of stem length to water depth, stem density, and forest density. These ecosystems can also create bed resistance by obstructing the flow of water through the forest, and may be more effective at protecting coastlines threatened by climate change than man-made structures. However, studies on storm surge wave attenuation and the ability of natural habitats to protect against damage are lacking. Approximately 35% of the world's mangrove forests have disappeared over the last two decades, and many of these ecosystems are at risk of being submerged due to sea level rise. Therefore, it is important to have data on the density and width of trees planted, diameter of trunks and roots, floor shape, bathymetry, and spectral features of waves to maintain the protective function of mangroves.

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