

Numerical Analysis of Wave Attenuation by Mangrove Forests

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Abstract— Mangrove forests provide natural coastal protection by attenuating wave energy, although their protective effectiveness remains challenging to quantify. In particular, the contributions of vegetation density and of the bulk drag coefficient are seldom separated, and open-source wave-resolving models are rarely checked against prototype-scale physical-model data. This study aims to quantify wave attenuation across a mangrove band at its seaward edge ($x = 35$ m), its middle ($x = 44$ m) and its landward edge ($x = 52$ m); to isolate the independent effects of vegetation density and of the drag coefficient (C_d); and to assess the consistency of the model against a prototype-scale physical benchmark. The XBeach numerical model was applied in non-hydrostatic (wave-resolving) mode to a 104 m numerical flume, with vegetation schematised into root, trunk and canopy layers, each with its own stem diameter, density and drag coefficient. Simulations were performed for three scenarios — no mangroves, low-density mangroves ($N = 25$ stems m^{-2}) and high-density mangroves ($N = 50$ stems m^{-2}) — with additional sensitivity tests varying the drag coefficient ($C_d = 2.0$ and $C_d = 1.5$). The analysis focused on three key wave parameters: water level, zero-crossing wave height, and significant wave height. Results show that high-density mangroves reduce the band-averaged significant wave height by 24%, whereas low-density mangroves achieve a 15% reduction compared with unvegetated conditions, so halving the stem density approximately halves the reduction. Lowering the drag coefficient to $C_d = 2.0$ and $C_d = 1.5$ reduced the attenuation to 18% and 17%, a monotonic but sub-linear dependence, matching the trend observed in a prototype-scale physical model experiment. These findings highlight the significant influence of vegetation density and drag on wave attenuation and support the use of mangroves as effective nature-based solutions for coastal defence and sustainable coastal management.

Keywords— mangrove, numerical model, wave attenuation, wave height reduction, XBeach.

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I. INTRODUCTION

Mangrove forests play a crucial role in coastal protection by dissipating wave energy, reducing erosion, and mitigating storm impacts. These unique ecosystems, located along tropical and subtropical shorelines and covering approximately 150,000 km^2 of the world's coastlines [1], act as natural barriers that help mitigate coastal erosion and reduce the impact of extreme waves such as storm surges and tsunamis [2] [4]. The structural complexity of mangrove, which is characterized by dense root networks and above-ground biomass, contributes to the ability to dissipate ocean wave energy [5] [7] (see Figure 1 for the global distribution). While numerous studies have demonstrated the role of mangrove forests in wave attenuation [9]–[13], quantifying the specific effects of vegetation density and drag coefficients on wave energy dissipation remains a challenge. Quantifying these effects experimentally is, however, costly: even prototype-scale physical models

— such as the large wave-flume study of Kelty et al. [14] — can span only a limited set of density, drag and hydrodynamic combinations because of the expense of construction and facility time. Numerical models can explore this parameter space far more economically, but their predictions require validation against physical-model data before they can be relied upon. Recent studies have further advanced and applied vegetation-wave modelling: De Dominicis et al. [15] showed at delta scale that mangroves can deliver measurable coastal defence in the Pearl River Delta. In parallel, experimental and field studies continue to constrain the bulk drag coefficient that governs this dissipation [16], [17]. However, the independent effects of vegetation density and the layer-resolved drag coefficient are seldom isolated, and few numerical studies have been validated directly against prototype-scale physical-model data [14].

Three specific problems follow from this. First, vegetation density and the bulk drag coefficient normally vary together — in the field they co-vary with species, stand age and site conditions — so their separate contributions to wave-energy dissipation cannot be attributed from field records alone. Second, the bulk drag coefficient is not a measurable property of the plant but a calibration parameter that absorbs the unresolved geometry of the prop-root network, and reported values span a wide range [16], [17], [18], which leaves predictions sensitive to a quantity that is rarely constrained. Third, most reduced-scale laboratory tests are subject to the Froude–Reynolds conflict, in which preserving Froude similarity for the free surface distorts the Reynolds-dependent drag on the stems [14], so the

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wave-height reductions they report cannot be transferred directly to prototype conditions. Taken together, these problems mean that although the qualitative role of mangroves is well established, coastal engineers still lack an inexpensive and defensible tool for quantifying how much protection a given forest configuration actually delivers.

To address these gaps, this study employs the XBeach numerical model to evaluate how mangrove vegetation influences wave attenuation under varying

densities and drag coefficient conditions. Unlike previous studies that primarily relied on empirical models, this research integrates numerical simulations with physical model comparisons to enhance the accuracy of wave attenuation predictions [19], [20]. By testing different vegetation densities and drag coefficients, this study aims to provide quantitative insights into the effectiveness of mangrove forests as nature-based coastal defense strategies.

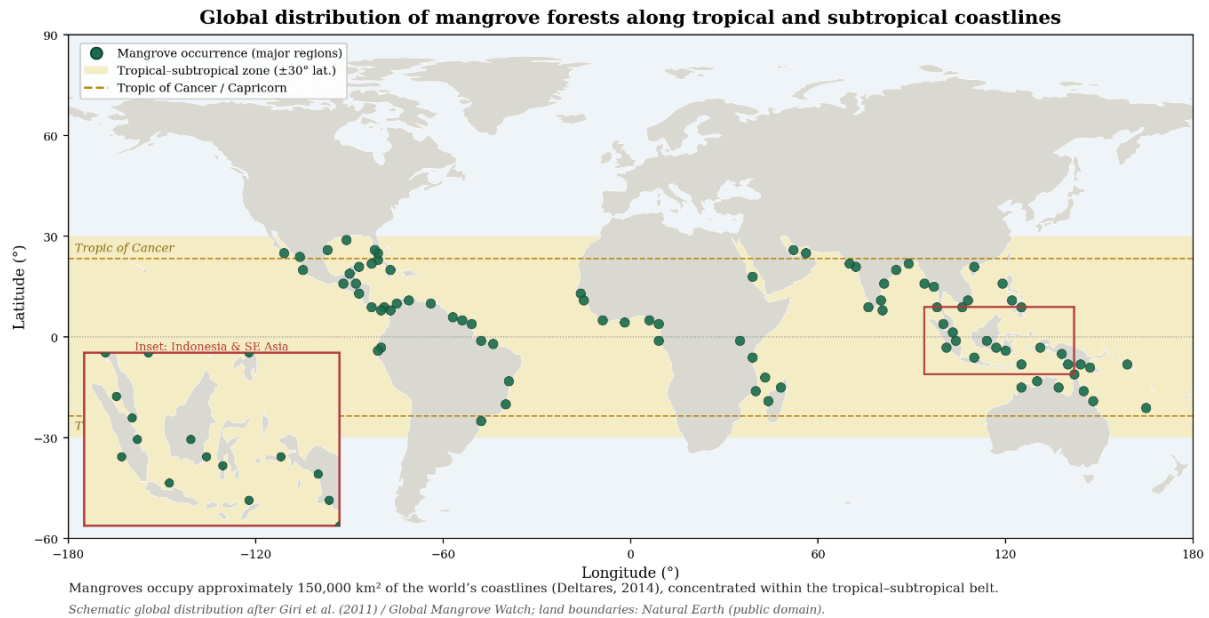


Figure 1. Global distribution of mangrove forests (~150,000 km²; [1]). Boundaries: Natural Earth; distribution after Global Mangrove Watch / Giri et al. [8].

This study simulates wave interactions with mangrove forests by varying vegetation density and drag coefficients in a numerical wave tank model. The setup follows the experimental framework of Kelty et al. [14] and uses their results as an aggregate benchmark for comparison. The outcomes will provide key insights for coastal engineers and policymakers designing mangrove-based flood mitigation strategies.

The primary objective of this study is to evaluate the effectiveness of mangrove forest in wave attenuation energy at different points in mangrove band. Specifically, wave attenuation at the beginning ($x = 35$ m), middle ($x = 44$ m), and end ($x = 52$ m) of mangrove forest band were analyzed. Comparing simulation results with large-scale experimental results aims to validate the model setup and provide valuable information into the potential of numerical simulation for studying mangrove forest as a natural defense mechanism.

The contribution of this study is therefore not the qualitative finding that denser or higher-drag vegetation attenuates more wave energy, which is well established, but a validated and transferable numerical framework. Specifically, this study (i) demonstrates that an open-source, wave-resolving model (XBeach in non-hydrostatic mode) reproduces, at the aggregate level, the wave-height reduction reported by the prototype-scale physical experiment of Kelty et al. [14]; (ii) isolates the independent effects of vegetation density and the layer-resolved drag coefficient through controlled numerical runs; and (iii) provides a transferable framework that,

once validated, enables inexpensive exploration of vegetation and hydrodynamic configurations that are impractical to reproduce physically. These capabilities support coastal-management strategies that leverage mangroves for sustainable, nature-based coastal protection.

II. LITERATURE REVIEW

This section reviews the evidence base on which the present numerical analysis rests. It is organised around the three elements of the article's title and objective: the observed magnitude of wave attenuation by mangrove forests (Section II.A), the numerical approaches available to reproduce it (Section II.B), and the bulk drag coefficient that governs the vegetation dissipation term (Section II.C). Section II.D synthesises the gap that this study addresses.

A. Wave Attenuation by Mangroves: Field and Laboratory Evidence

Field measurements consistently show that mangrove forests attenuate incident waves, but the reported rates vary widely with forest structure, water depth and incident wave conditions. Mazda et al. [5] measured wave reduction across a *Sonneratia*-dominated forest and attributed most of the dissipation to drag on the trunks and pneumatophores. Phuoc and Massel [6] observed a coupled reduction of wave energy and suspended sediment concentration across the Can Gio forest in southern Vietnam, while Bao [9] related the attenuation

rate to forest structure along the Vietnamese coast and Horstman et al. [10] quantified the cross-shore decay of wave energy in Trang, Thailand. Reviews by Hashim et al. [11], Amma and Bhaskaran [4] and, more recently, Temmerman et al. [21] converge on the conclusion that mangroves are effective wave and surge buffers, and comparable behaviour has been reported in the Nanliu Delta [22] and off Mumbai [23]. What all of these datasets share, however, is that forest density, species composition and hydrodynamic forcing co-vary from site to site, so the sensitivity of attenuation to any single vegetation property cannot be extracted from them.

Controlled laboratory work removes this co-variation but introduces a scale problem. Hoque et al. [12] examined wave attenuation by a coastal forest under storm surge in a flume, and Tomiczek et al. [24] investigated the parcel-scale effects of mangroves on wave transformation and force reduction. Most such tests are conducted at reduced scale, where Froude scaling of the free surface conflicts with Reynolds scaling of the stems and biases the drag [14]. Kelty et al. [14] addressed this directly with a prototype-scale physical model of a *Rhizophora* forest of moderate cross-shore thickness in a 104 m large wave flume, combining LiDAR-based characterisation with Reynolds scaling. Their experiment reported wave-height reductions of the order of 13–28% for high-density random-wave conditions and is adopted here as the benchmark precisely because it is not subject to the scale distortion of smaller facilities. Even so, the construction cost and facility time of such experiments limit the number of density, drag and hydrodynamic combinations that can be covered, which is the reason numerical models remain necessary.

B. Modelling Approaches for Wave–Vegetation Interaction

Numerical treatments of wave–vegetation interaction fall into two broad families. Phase-averaged models solve a wave-action or wave-energy balance and represent vegetation as a spectral dissipation term. The formulation of Dalrymple et al. [25] for wave diffraction due to areas of energy dissipation underlies most of them; Mendez and Losada [26] extended it empirically to random breaking and non-breaking waves over vegetation fields, and Suzuki et al. [18] introduced the vertical layer schematisation into SWAN, which allows roots, trunk and canopy to be assigned separate diameters, densities and drag coefficients. Wu et al. [27] showed that resolving such vertical density variations materially changes the predicted attenuation. Magdalena et al. [13] applied non-linear shallow-water equations to quantify attenuation in Manila Bay, Chen et al. [28] improved the representation of mangroves in storm-surge modelling, and at delta scale De Dominicis et al. [15] demonstrated that mangroves can deliver measurable coastal defence in the Pearl River Delta. Phase-averaged models are computationally cheap and appropriate for regional application, but they return only the short-wave envelope, so wave-by-wave statistics cannot be recovered from them.

Phase-resolving (wave-resolving) models instead solve the non-linear shallow-water equations together

with a non-hydrostatic pressure correction and therefore resolve individual waves. SWASH [29] is the archetype of this family; XBeach provides an equivalent one-layer non-hydrostatic mode [19], in which van Rooijen et al. [30] implemented a layer-resolved Morison-type drag force added directly to the momentum equations. This is the formulation adopted here, because the stated objective requires significant wave heights derived from wave-by-wave surface-elevation records at fixed cross-shore gauges. XBeach has previously been applied by the present authors to related wave-driven processes [20], which supports its use in the present configuration.

C. The Bulk Drag Coefficient

In every drag-based formulation the bulk drag coefficient C_d is the parameter that carries the unresolved complexity of the plant. It is not a directly measurable plant property: it absorbs the geometry of the prop-root network, the wake interaction between neighbouring elements and the Reynolds dependence of the flow around them. Yoshikai et al. [16] measured drag in a planted *Rhizophora* forest in the field and proposed a predictive relation for it, while Reis et al. [17] determined drag coefficients experimentally for flexible vegetation under non-breaking waves. Reported values differ systematically by species, by layer and by flow regime, and no consensus value exists for *Rhizophora* prop roots. Because the vegetation force scales linearly with C_d (Eq. 4), this uncertainty propagates directly into the predicted wave-height reduction, which is why the present study treats C_d as a controlled variable (Runs 2, 4 and 5) rather than as a single calibrated constant.

D. Synthesis and Research Gap

Taken together, the literature establishes four points. First, mangroves attenuate waves at rates that vary by close to an order of magnitude across sites. Second, vegetation density and the drag coefficient are both first-order controls, yet published studies rarely vary them independently. Third, prototype-scale physical evidence exists [14] but is expensive and necessarily limited in coverage. Fourth, wave-resolving numerical models with layer-schematised vegetation [19], [30] can in principle fill this gap, but have seldom been checked against prototype-scale data. Within the Indonesian context, this journal has published closely related coastal-protection and mangrove studies, including physical-model work on wave reflection from armour units on seawall structures [31], hydrodynamic modelling of a port approach channel [32], and remote-sensing assessment of mangrove carbon stocks under climate variability [33]; the wave-attenuation function of mangrove forests, however, has not yet been addressed there with a wave-resolving vegetation model benchmarked at prototype scale. The present study addresses this gap directly.

The novelty of this work lies in the combination of these three elements rather than in any one of them. To the authors' knowledge, this is the first study to reproduce the prototype-scale mangrove wave-flume experiment of Kelty et al. [14] using an open-source, wave-resolving model with a layer-schematised vegetation formulation and, on that basis, to separate the density control from the drag-coefficient control within a single, internally consistent numerical campaign in

which the bathymetry, the forcing and all remaining vegetation properties are held exactly constant. Because the model is configured directly at prototype scale, the Froude–Reynolds conflict identified above does not arise, so the parameter sensitivities reported here are transferable to real forests rather than being tied to a particular laboratory scale.

III. METHOD

This section provides a detailed description of the numerical model setup, simulation scenarios, and the methods used to analyze wave attenuation effects. This study is based entirely on numerical simulations performed with XBeach; the flume geometry and wave forcing replicate the prototype-scale physical-model experiment of Kelty et al. [14], and no new physical experiments were conducted, so all results reported herein are numerical. The following subsections outline the configuration of the flume, vegetation model, and wave analysis to ensure accurate simulation of the interaction between mangrove forests and wave dynamics.

A. Model Setup

Figure 2 shows the numerical setup used in this study (not to scale). In the plan view (Figure a), the layout of

the flume is displayed, showing various sections and their respective lengths in meters. The initial water level was set to 0.73 meters from the bed for every run, and the cross-section view (Figure b) shows a detailed profile of the flume. A 7-meter-long foreshore with a slope of 1:12 is positioned at the beginning of the flume. Vegetation, representing mangrove forest, is located along a 17-meter stretch from $x = 35$ meters to $x = 52$ meters. A beach with a slope of 1:12 is positioned at the end of the flume. These configurations are based on parameters set by the flume experiment (x - y - $z = 104$ m $\times$ 3.6 m $\times$ 3.6 m) to replicate conditions observed in the referenced studies. At the grid resolution used (0.5 m horizontal spacing), the 1:12 foreshore and beach slopes correspond to a bed-level change of only about 0.04 m per grid cell, so the sloping bathymetry is smoothly resolved without staircase artefacts. Numerical stability was ensured by an adaptive time step constrained to a maximum Courant number of 0.7, which was satisfied throughout each simulation. For the imposed peak period ($T_p = 3.0$ s) in 0.73 m of water, the peak wavelength is about 7.6 m, so the 0.5 m grid resolves the waves with roughly 15 cells per wavelength, which is adequate for the non-hydrostatic solver.

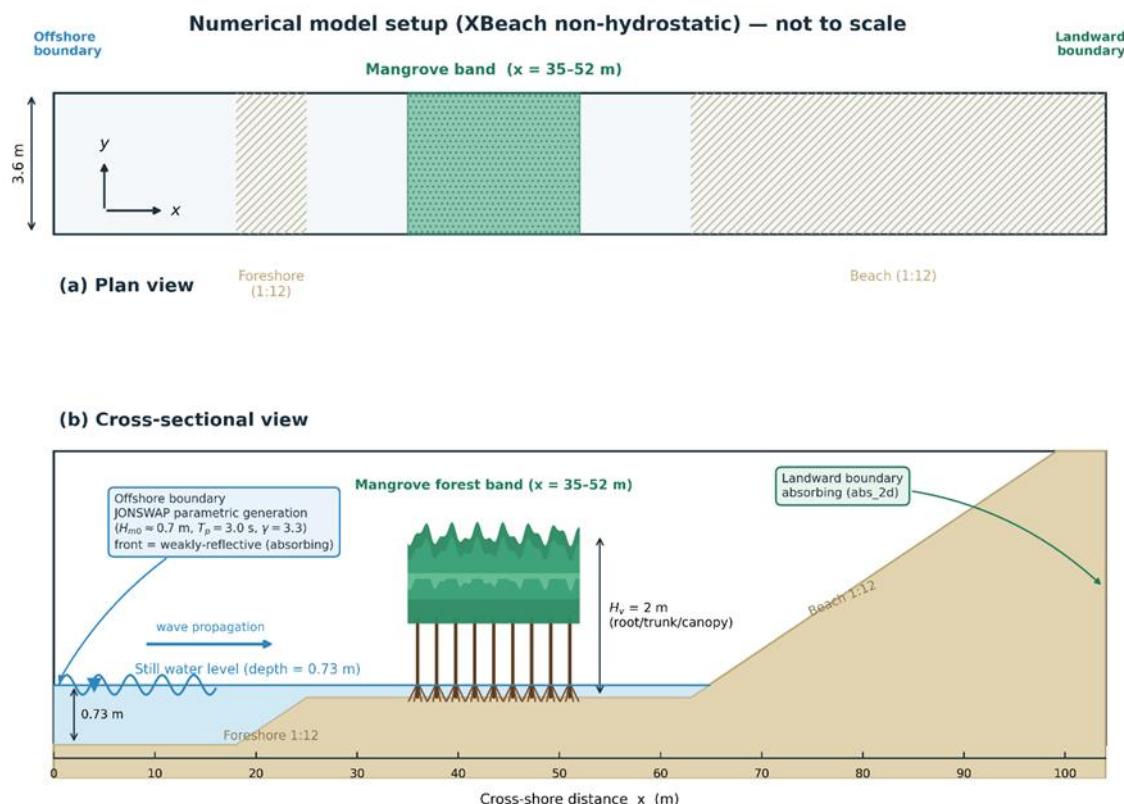


Figure 2. Numerical model setup based on the experimental setup (not to scale): (a) plan view of the flume; (b) cross-sectional view of the flume.

This The simulation employs a structured grid with 0.5 m $\times$ 0.5 m cells. The model was run in XBeach non-hydrostatic (wave-resolving) mode, in which the non-linear shallow water equations are solved together with a non-hydrostatic pressure correction (analogous to a one-layer SWASH formulation [29]), so that the propagation and decay of individual waves are resolved. This wave-resolving mode was required because the analysis relies

on wave-by-wave surface-elevation time series extracted at fixed cross-shore gauges, from which significant wave heights are obtained; such individual-wave statistics cannot be recovered from the phase-averaged (surfbeat) solution, which yields only the short-wave envelope. In this mode the wave-action balance is not used; instead, vegetation is represented as a drag force added directly to the momentum equations and schematised into

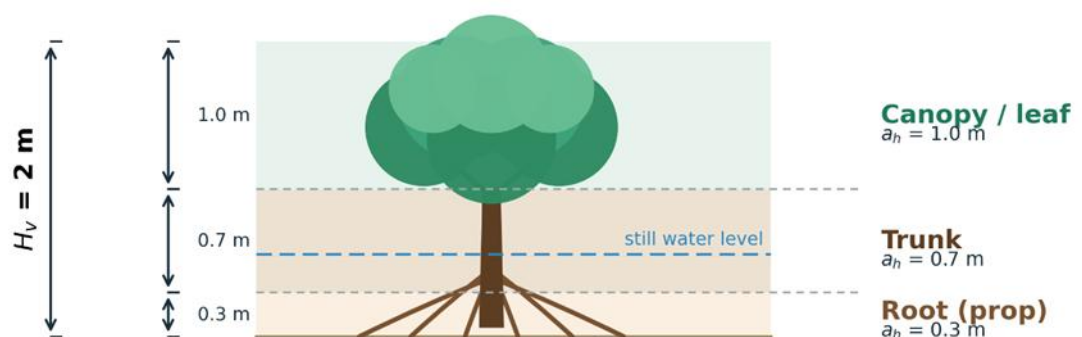
vertical layers (root, trunk, and canopy) following van Rooijen et al. [30], with a bulk drag coefficient, stem diameter, and stem density specified for each layer (Eqs. 2–5). Waves were imposed at the offshore boundary as a JONSWAP spectrum (significant wave height $H_{m0} \approx 0.7$ m, peak period $T_p = 3.0$ s, peak-enhancement factor $\gamma = 3.3$, directional spreading $s = 1000$, shore-normal at 270°), generated to first order (order = 1) with a weakly-reflective (absorbing) offshore boundary so that reflected energy radiates out of the domain. Surface elevation was stored at 1 s intervals (output Nyquist 0.5 Hz) at the gauges $x = 35, 44$ and 52 m. In this setup, the parameter $\text{posdwn} = 1$ is used, where positive depth values represent areas below the water level, and negative values indicate elevations above it. Mangrove vegetation is assigned within the $x = 35$ m to $x = 52$ m range using a separate input file that specifies vegetation presence. In this file, the code '1' is used to designate the cells containing mangrove vegetation. Different mangrove densities are implemented through the vegetation density parameter N : the high-density and low-density configurations use $N = 50$ and $N = 25$ respectively (Table 2), while all other vegetation properties are held constant. Here N denotes the number of vegetation stems per unit horizontal area (stems m^{-2}) in the XBeach vegetation module [19]. This setup allows for precise modeling of mangrove influence on wave dynamics and energy dissipation along the designated section of the simulation domain. Every simulation run is set to a duration of 1 hour (3600 seconds). A complete summary of the model setup parameters is given in Table 1. Figure 3 shows the sectional definitions (referred to as functions $nsec$ or $npts$) of mangrove tree as modeled in XBeach. In this study, vegetation was divided into three distinct

parts, including root, trunk, and leaf. Each section is modeled to capture the unique characteristics and interactions of mangrove with wave dynamics. The heights of these parts are 0.3 m, 0.7 m, and 1 m for root, trunk, and leaf respectively, and therefore the total height of vegetation (H_v) is 2 m. These geometries represent the typical size of adult mangrove and are consistent across all simulation runs.

TABLE 1.
XBEACH MODEL SETUP PARAMETERS.

Parameter	Value / setting
Model & mode	XBeach, non-hydrostatic (nonh = 1)
Grid resolution ($\Delta x = \Delta y$)	0.5 m
Domain ($x \times y$)	104 m $\times$ 3.6 m
Computational time step (Δt)	Adaptive, CFL-limited (CFL = 0.7, default)
Still-water depth	0.73 m ($\text{posdwn} = 1$)
Foreshore / beach slope	1:12 / 1:12
Mangrove band	$x = 35\text{--}52$ m
Vegetation height H_v	2 m (root 0.3, trunk 0.7, leaf 1.0)
Stem diameter b_v (per layer)	see Table 2
Vegetation density N	50 (HD) / 25 (LD) stems m^{-2}
Drag coefficient C_d (per layer)	see Table 2 (1.5–3.5)
Wave boundary condition	JONSWAP; $H_{m0} \approx 0.7$ m; $T_p = 3.0$ s; $\gamma = 3.3$
Offshore boundary	Parametric generation; front = default absorbing
Landward boundary	Default absorbing (abs_2d)
Incident/reflected separation	None (order = 1)
Bottom friction	XBeach default
Morphology	Off (morphology = 0; sedtrans = 0)
Simulation duration	3600 s (1 h)

Mangrove vegetation schematisation in XBeach — three vertical layers



Each layer i is assigned a stem diameter $b_{v,i}$, element density N and bulk drag coefficient $C_{d,i}$ (Table 1).

Figure 3. Mangrove specification (root, trunk and canopy layers) as defined in the model.

In addition to these height specifications, the stem diameter of mangrove (referred to by the function b_v) was varied to simulate different drag coefficient scenarios (represented by the function C_d). This approach allows the study to assess how variations in mangrove stem diameter influence wave attenuation through different drag coefficients (Table 2).

B. Simulation Scenario

Table 2 summarizes the different simulation runs conducted in this study to assess the influence of mangrove vegetation on wave attenuation. Five simulation runs were conducted:

- 1) Run 1: No vegetation (baseline)
- 2) Run 2: High-density mangrove
- 3) Run 3: Low-density mangrove

4) Run 4: High-density mangrove with reduced drag coefficient

5) Run 5: High-density mangrove with further reduced drag coefficient

TABLE 2.
SIMULATION SCENARIOS DETAIL.

Run	Observed Parameter	Vegetation's presence	Vegetation density (N)	Vegetation height (a _n)	Stem diameter (b _v)	Drag coefficient (C _d)
1	Mangrove presence	0 (deactivated)	50	0.3; 0.7; 1	0.0286; 0.176; 0.03	3.5; 3.5; 1
2	Mangrove presence	1 (activated)	50	0.3; 0.7; 1	0.0286; 0.176; 0.03	3.5; 3.5; 1
3	Variation of mangrove's density (Run 2 and 3)	1	25	0.3; 0.7; 1	0.0286; 0.176; 0.03	3.5; 3.5; 1
4	Variation of drag coefficient (Run 2, 4, and 5)	1	50	0.3; 0.7; 1	0.0286; 0.1; 0.03	2; 2; 1
5	Variation of drag coefficient (Run 2, 4, and 5)	1	50	0.3; 0.7; 1	0.0286; 0.056; 0.03	1.5; 1.5; 1

Each run examines specific observed parameters by varying the presence of vegetation, vegetation density (caller function N), stem diameter, and drag coefficient. These runs are designed to isolate and observe the impact of specific variables on the effectiveness of mangrove in attenuating wave energy, thereby providing a comprehensive understanding of the factors influencing this natural coastal protection mechanism.

The first two runs (Runs 1 and 2) compare the presence versus absence of mangrove to understand their basic influence on wave attenuation. Run 3 examines the impact of halving vegetation density relative to Run 2, providing valuable information on how changes in density affect wave energy dissipation. Runs 4 and 5 explore the effects of reducing the drag coefficient in different increments compared to Run 2, shedding light on the role of the drag coefficient in wave attenuation process.

C. Wave Statistics

To thoroughly analyze wave attenuation effects of mangrove forest, it is essential to process wave data accurately. The key wave statistics examined in this study include water level time series, wave height, and significant wave height. These parameters provide a comprehensive understanding of wave characteristics and the interaction with mangrove vegetation.

Water level time series data were collected at multiple points along the flume, specifically at the beginning (x = 35 m), middle (x = 44 m), and end (x = 52 m) of mangrove band. These points were selected to capture the changes in wave characteristics as waves propagate through mangrove forest. The data were recorded at regular intervals to ensure a high temporal resolution, allowing for detailed analysis of wave transformation over time.

The recorded water level data were then processed to remove any noise and to identify the individual wave events. This was achieved using a filtering technique to smooth out minor fluctuations and a peak detection algorithm to pinpoint the crests and troughs of each wave. This process enabled the accurate calculation of wave heights and periods for subsequent analysis.

Wave height is an important parameter for understanding the energy carried by the waves. It is defined as the vertical distance between the crest (highest point) and the trough (lowest point) of a wave.

Analyzing wave heights at various points in the flume shows how mangrove vegetation impacts wave energy dissipation.

Wave heights were calculated from water level time series data using a zero-crossing method. This method involves identifying the points where water level crosses the mean water level (zero-crossings) and measuring the vertical distance between successive crests and troughs. This approach provides a reliable estimate of wave height for each wave event in the time series.

Significant wave height (H_s) is a statistical measure representing the average height of the highest one-third of waves in a given wave record. It is widely used in coastal engineering to describe wave conditions, as it provides a meaningful representation of the wave energy.

To calculate H_s, wave heights identified in the previous step were sorted in descending order. The highest one-third of these wave heights were then averaged to obtain H_s. This statistic was calculated for each of the measurement points (x = 35 m, x = 44 m, x = 52 m) to evaluate the attenuation effect of mangrove forest on the most energetic waves. The formula to calculate the significant wave height is:

$$H_s = \frac{1}{N} \sum_{i=1}^N H_{(i)} \quad (1)$$

where:

H_s = significant wave height

H(i) = represents the individual wave heights, sorted in descending order

N = number of the highest one-third of the waves

D. Vegetation Model

In the non-hydrostatic mode the vegetation is not represented through spectral wave-energy dissipation; instead it exerts a drag force added directly to the depth-averaged momentum equations [25], [30]. Each plant is schematised into three vertical layers — roots, trunk and canopy — following the vertical-layer schematisation of van Rooijen et al. [30], with a stem diameter b_v, element density N and bulk drag coefficient C_d specified per layer (Table 2). The model solves the depth-averaged continuity and momentum equations with a non-hydrostatic pressure term:

$$\frac{\partial \eta}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial \eta}{\partial x} - \frac{1}{\rho} \frac{\partial \bar{q}}{\partial x} - \frac{\tau_{b,x}}{\rho h} - \frac{F_{v,x}}{\rho h}$$

where η is the surface elevation, h the water depth, (u, v) the depth-averaged velocities, $\bar{q}$ the depth-averaged non-hydrostatic pressure, $\tau_{b,x}$ the bed shear stress and $F_{v,x}$ the vegetation drag force per unit horizontal area (the y-momentum equation is analogous). The vegetation force is obtained by summing a layer-resolved Morison-type drag over the n_v vegetation layers:

$$F_{v,x} = \frac{1}{2} \rho \sum_{i=1}^{n_v} C_{d,i} b_{v,i} N_i \alpha_i |u|$$

$$\alpha_i = \min(a_{h,i}, h)$$

where ρ is the water density, $|u|$ the local flow speed (predominantly cross-shore in the flume), $a_{h,i}$ the height of layer i and α_i its wetted height, so that the formulation applies to both submerged and emergent vegetation. The bulk drag coefficient $C_{d,i}$ is the only calibrated parameter and is varied in Runs 2, 4 and 5 (Table 2).

IV. RESULTS AND DISCUSSION

The results section presents the key findings of this study, beginning with a preliminary check of lateral uniformity that justifies the two-dimensional modelling choice, followed by water level fluctuations and wave energy dissipation along the mangrove band. The following subsections delve into the specific outcomes of the numerical simulations, with particular focus on water level time series and significant wave heights as waves propagate through the mangrove forest.

A. Influence of Flume Width

Water level profiles along the flume length are analyzed to assess variations in wave energy dissipation across different reference points in the y direction, as shown in Figure 4. This is aimed to determine whether the location of referenced points in the y direction significantly influences the observed water level fluctuations. The referenced points are captured at minute 10 for several points in width ($y = 0.5$ m, $y = 2$ m, and $y = 3.5$ m) along the x -axis. Subsequently, the analysis showed that water level profiles at the sides and center of the flume exhibited minimal differences, with a standard deviation of less than 2%.

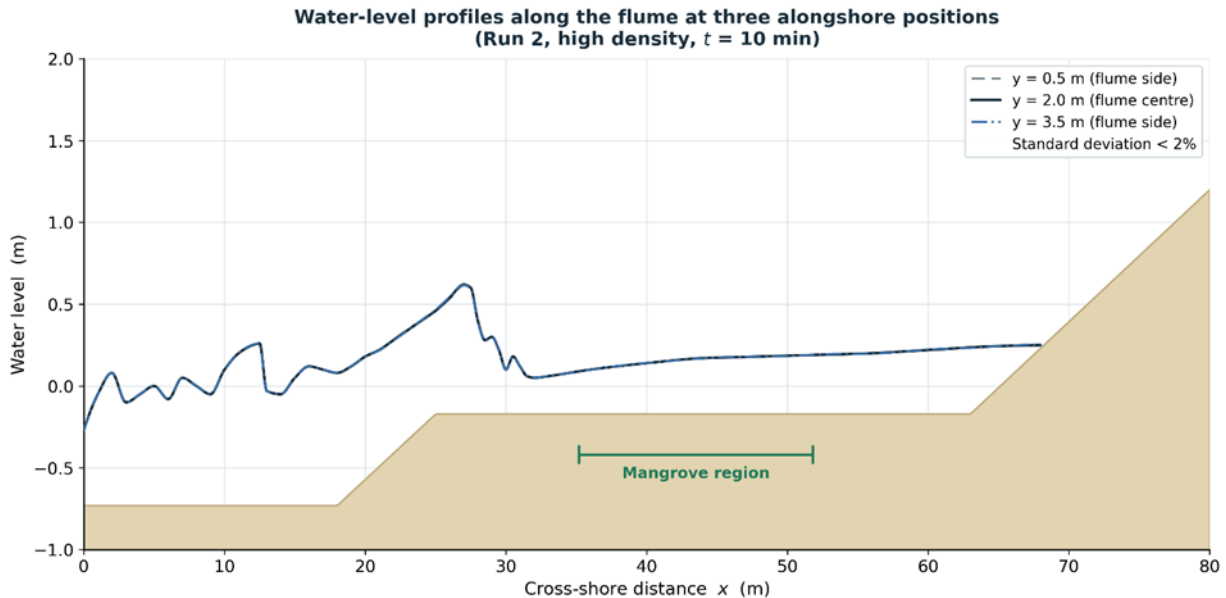


Figure 4. Water-level profiles along the flume length at different alongshore positions ($y = 0.5, 2.0$ and 3.5 m).

This uniformity indicates that the placement of referenced points in the flume has negligible effects on the measured water level dynamics, confirming that the results are effectively one-dimensional. The two-dimensional domain was nonetheless adopted to correspond directly to the 3.6-m-wide physical flume of Kelty et al. [14] and to verify this lateral uniformity explicitly; given the confirmed absence of significant lateral variation, a one-dimensional cross-shore configuration would be a more computationally efficient alternative for future runs.

B. Water Level Time Series

Water level time series and significant wave heights are analyzed along mangrove band at specific points, including the beginning ($x = 35$ m), middle ($x = 44$ m), and end ($x = 52$ m). These three stations were selected to capture the cross-shore decay of wave energy from the seaward to the landward edge of the forest. At the center of the flume, focusing on Run 2 (high-density mangrove) of the simulations (see Figure 5). These locations are selected to capture variations in wave energy dissipation as waves propagate through mangrove forest.

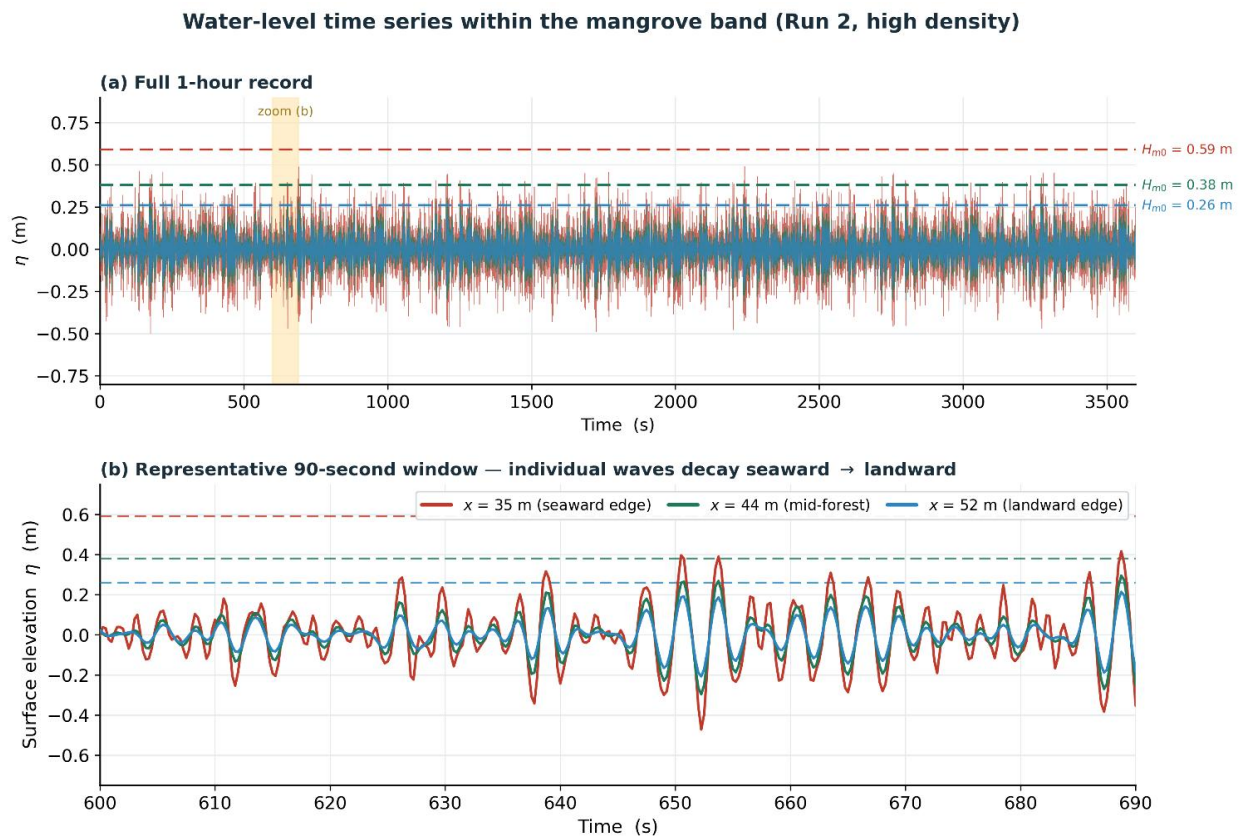


Figure 5. Water-level time series for Run 2 (high-density) at the gauges within the mangrove band: (a) full 1-hour record; (b) 90 s windows within mangrove band.

At the beginning of mangrove band ($x = 35$ m), water level time series exhibited visible fluctuations, reflecting the interaction of incoming waves with vegetation. Initially, significant wave height (H_s) is observed to be higher (0.59 m), showing wave energy entering mangrove area. As waves propagate further into mangrove forest, there is a discernible decrease in water level fluctuations. This reduction can be attributed to the dissipation of wave energy by mangrove vegetation, which acts as a natural barrier.

In the middle of mangrove band ($x = 44$ m), water level time series continues to show moderated fluctuations compared to the initial measurement point. In this scenario, H_s ($= 0.38$ m) demonstrates a further decrease, underscoring the cumulative effect of vegetation in attenuating wave energy. The dense root networks and above-ground biomass of mangrove play an important role in absorbing wave energy, thereby mitigating the impacts of high-energy waves on the coastal shoreline.

Towards the end of mangrove band ($x = 52$ m), water level time series shows minimal fluctuations, indicating significant wave energy dissipation. H_s ($= 0.26$ m) which is reduced compared to earlier points, highlighting the effectiveness of mangrove forest in attenuating wave energy across the width. This observation is in line with the expected pattern of wave energy dissipation as waves propagate through vegetated coastal zone, emphasizing the importance of mangrove as natural coastal defense.

In general, the analysis of water level time series and significant wave heights along mangrove band in Run 2 shows a progressive decrease in wave energy from the beginning to the end of mangrove forest. These findings reinforce the effectiveness of mangroves as natural coastal defenses, supporting previous research [14]. The study provides quantitative evidence that can inform coastal restoration and policy-making efforts.

C. Significant Wave Heights (H_s) along the Band

Figure 6 shows the cross-shore evolution of the significant wave height through the mangrove forest, expressed as $H_{m0}(x)$ normalised by its value at the seaward edge, $H_{m0}(x = 35$ m). Presented this way, the data isolate the progressive decay of wave energy through the forest and place all runs on a common, dimensionless basis: every run equals unity at the entry station by definition and decreases landward, with the high-density run (Run 2) showing the steepest decline. Because the bathymetry is identical across runs, the separation between the no-vegetation run (Run 1) and the vegetated runs at each station is the attenuation attributable to the mangroves. In the high-density run the wave height falls from $H_{m0} = 0.59$ m at the entry ($x = 35$ m) to 0.26 m at the exit ($x = 52$ m), a through-forest transmission $K_t = H_{m0}(52)/H_{m0}(35) = 0.45$; these absolute values, the transmission coefficient, and the band-averaged reduction relative to Run 1 are summarised in Table 3.

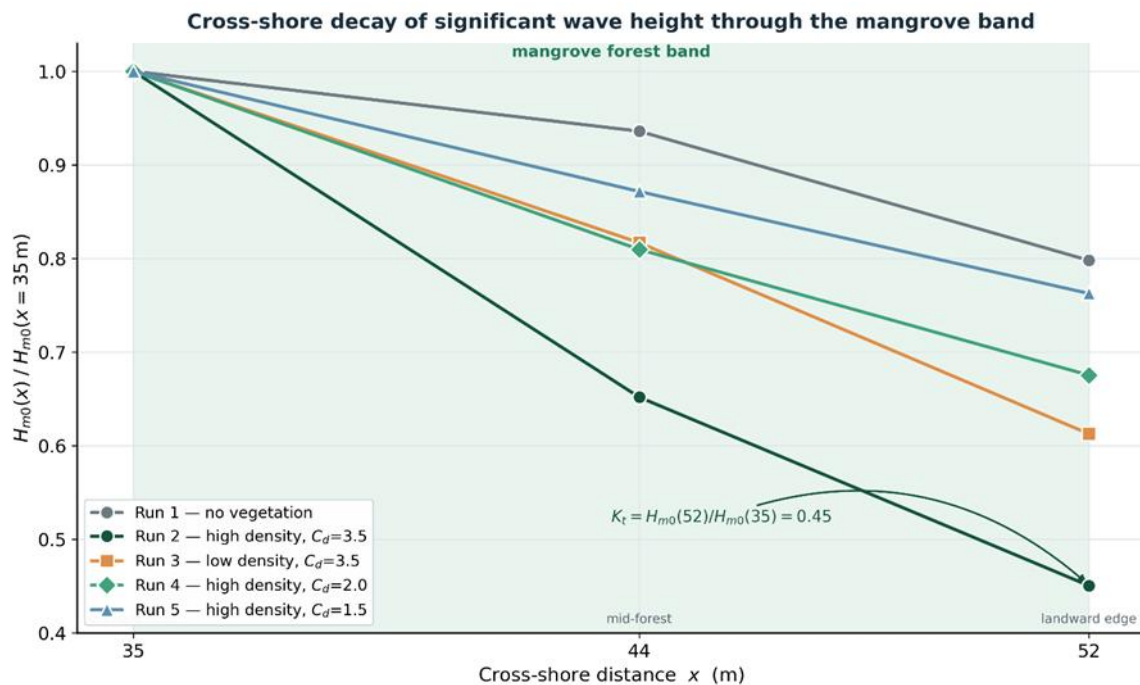


Figure 6. Significant wave heights (H_{m0}) along the band: cross-shore decay for Runs 1–5.

TABLE 3.
RELATIVE SIGNIFICANT WAVE HEIGHTS (H_{si}/H_v) ALONG MANGROVE BAND.

Run	Beginning ($x = 35$ m)	Middle ($x = 44$ m)	End ($x = 52$ m)	Average	Relative wave height reduction
1	0.297	0.278	0.237	0.271	0%
2	0.293	0.191	0.132	0.205	–24%
3	0.284	0.232	0.174	0.230	–15%
4	0.268	0.217	0.181	0.222	–18%
5	0.257	0.224	0.196	0.225	–17%

Relative significant wave height = H_{si}/H_v , where $H_v = 2$ m. The minus sign (–) marks the height reduction relative to Run 1.

This The differences between runs reflect vegetation presence, density and the drag coefficient. Density is the dominant control: the low-density run (Run 3) gives a band-averaged reduction of 15% against 24% for high density, so halving the stem density roughly halves the reduction. Runs 2, 4 and 5 isolate the bulk drag coefficient at fixed high density — Run 2 ($C_d = 3.5$ for the root and trunk layers) gives 24%, Run 4 ($C_d = 2.0$) gives 18%, and Run 5 ($C_d = 1.5$) gives 17% — a monotonic trend (higher C_d , greater attenuation) that follows directly from the drag-force formulation, in which the vegetation force scales linearly with C_d .

The frequency-domain counterpart of this energy decay is shown by the wave energy density spectra at the offshore boundary and at the three in-forest gauges ($x = 35$, 44 and 52 m) for all five runs (Figure 7), where the spectral energy diminishes from the seaward to the landward edge of the forest.

D. Vegetation Presence

Table 3 presents the relative significant wave heights (H_{si}/H_v) measured at the beginning ($x = 35$ m), middle ($x = 44$ m), and end ($x = 52$ m) of mangrove band for different runs. H_{si} is significant wave height for each run and H_v is vegetation height (= 2 m). Notably, a comparison between Run 1 (without vegetation) and Run 2 (with high-density vegetation) shows a marked relative height reduction in significant wave heights due to mangrove presence. Specifically, the average of relative

significant wave height in Run 1 ($H_{s1,av}/H_v$) is 0.271, while in Run 2, it is 0.205. This represents a 24% reduction in significant wave height along mangrove band, highlighting the effectiveness of mangrove vegetation in attenuating wave energy.

This study is consistent with the physical model study by Kelty et al. [14], which is used here as an aggregate benchmark. For random waves in a high-density forest, their prototype-scale experiment reported reductions in the range 13–28% (about 28% at the shallowest depth), so the present 24% is consistent at the aggregate level (Table 4). Two points are noted for transparency. First, the validation is necessarily aggregate: the numerical and physical wave fields cannot be made identical — open-boundary JONSWAP forcing in XBeach versus a piston wavemaker in a walled flume with a discretely-placed, idealized forest — and the benchmark reports aggregate decay and reduction rather than a dense measured profile, so a gauge-by-gauge error metric would rest on data the experiment did not resolve. Second, the relative wave height imposed here exceeds the non-breaking range tested by Kelty et al. [14] ($H_{m0}/h_v = 0.18$ – 0.36), so the present conditions include depth-induced breaking alongside vegetation dissipation; because the vegetation-attributable reduction is obtained by differencing against the no-vegetation baseline run, which carries the same breaking and friction, the reduction still isolates the mangrove effect, but the

agreement should be read as an indicative aggregate consistency rather than a strict reproduction of the benchmark's hydrodynamic regime. Reproducing a specific non-breaking Kelty case is identified as a clear

direction for future refinement. The overall behaviour is summarised in the Graphical Abstract (Figure 8).

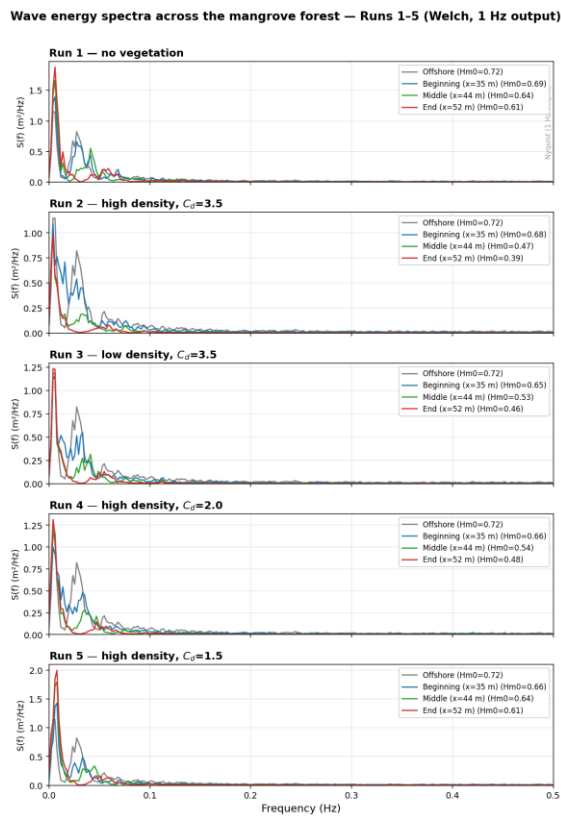


Figure 7. Wave energy density spectra across the mangrove forest for Runs 1–5 (Welch method), at the offshore boundary and at the in-forest gauges ($x = 35, 44$ and 52 m).

TABLE 4.
COMPARISON BETWEEN THE PRESENT NUMERICAL RESULTS AND THE PHYSICAL-MODEL RESULTS OF KELTY ET AL. [14].

Parameter	Present numerical model	Physical model (Kelty et al. [14])
Wave-height reduction, high-density mangrove	24%	13–28%
Wave-height reduction, low-density mangrove	15%	$\approx 16\%$
Difference between high- and low-density	9%	12%

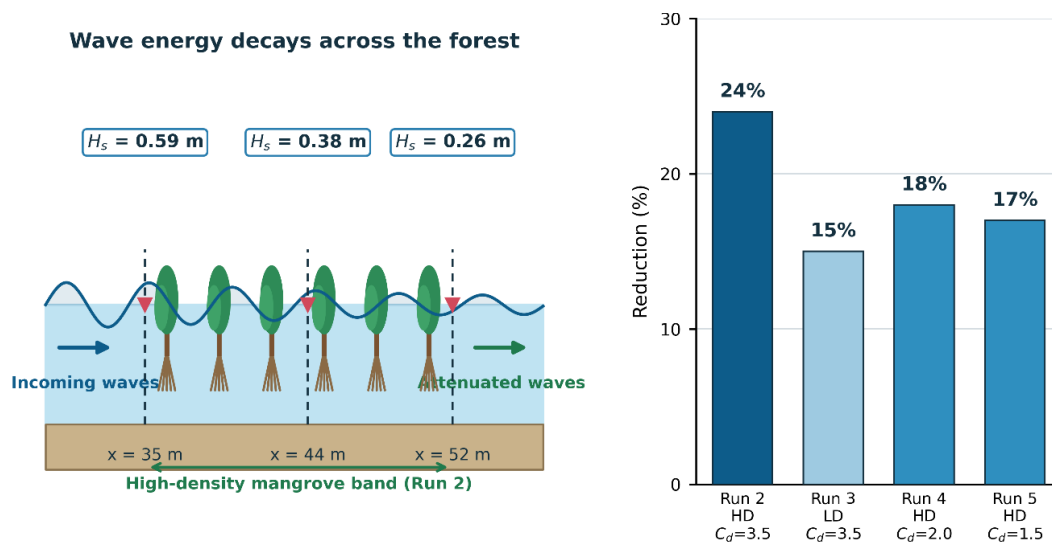


Figure 8. Graphical Abstract. Wave attenuation by mangroves: H_s decreases across the forest band; attenuation increases with density and drag coefficient

E. Vegetation Density and Drag Coefficient (C_d)

The comparison between Run 2 (high-density) and Run 3 (low-density) shows significant differences in wave height reduction, with relative reductions of 24% and 15% (9% difference) respectively. This empirical observation suggests that low-density mangrove dissipates wave energy to a lesser extent, as shown by Equation 4. This study is consistent with Kelty et al. [14], which demonstrated a comparable 12% difference in wave height reduction between high and low-density mangrove configurations. Slight differences may exist between physical and numerical models due to the placement of individual mangrove. The numerical simulation arranges mangrove trees in an orderly fashion (accounted as a model limitation), while the physical model positions them randomly.

In particular, Runs 2, 4, and 5 focus on the impact of varying drag coefficient C_d on wave attenuation. Run 2 features the highest drag coefficient scenario, with drag coefficient C_d of 3.5 for the root and trunk layers and 1 for the leaf layer. Run 4 uses a lower drag coefficient C_d of 2 for the root and trunk layers while keeping the leaf layer at 1. This run shows an average relative significant wave height ($H_{s4,av}/H_v$) of 0.222 and a relative reduction of 18%. However, the reduction is still significant because it is less pronounced than in Run 2, indicating that the lower drag coefficient results in decreased wave energy dissipation. Run 5 uses the lowest drag coefficient C_d of 1.5 for the root and trunk layers and maintains 1 for the leaf layer. This run has an average relative significant wave height ($H_{s5,av}/H_v$) of 0.225 and a relative reduction of 17%. The lower drag coefficient in this scenario leads to the least amount of wave energy dissipation among the three runs, confirming the trend that a higher drag coefficient corresponds to greater wave attenuation [14], [22], [23].

Determining the appropriate drag coefficient C_d is a challenging process, as the process requires specific tests and detailed information on hydrodynamic conditions and vegetation geometry. Drag coefficient (C_d) is influenced by multiple factors, including the flow regime, the morphology of vegetation, and the interaction between water flow and plant structure [16], [17]. Accurate determination of drag coefficient C_d necessitates precise measurements and modeling to capture these complex interactions effectively. This complexity underscores the need for thorough, site-specific studies to obtain reliable drag coefficient values for use in numerical simulations and coastal management practices.

On scaling, the physical benchmark of Kelty et al. [14] is itself a prototype-scale experiment conducted in a 104 m large wave flume, designed specifically to overcome the Froude–Reynolds conflict of reduced-scale vegetation tests, in which Reynolds similitude is lost under Froude scaling and the Reynolds-dependent drag coefficient is biased. Because the present model is configured at that prototype scale (domain, depth and vegetation), it operates in a realistic Reynolds regime, the free-surface waves satisfy Froude similarity, and no additional scale correction is required; Reynolds dependence enters only through the prescribed bulk C_d ,

so the use of a constant C_d per layer is the relevant simplification, bounded by the C_d sensitivity runs (Runs 2, 4 and 5). The results confirm that mangrove forests can serve as effective nature-based solutions for coastal protection. The higher attenuation rates observed in high-density mangrove conditions suggest that coastal restoration projects should prioritize dense planting strategies to maximize wave energy dissipation [34]. Furthermore, the sensitivity of wave reduction to drag coefficients highlights the need for site-specific calibration of numerical models to improve predictive accuracy for real-world applications.

F. Synthesis of the Findings, Novelty and Implications

Considered together, the five runs support a quantitative statement that neither the field literature nor the physical benchmark can make on its own: density and drag are both first-order controls, but they are not equally influential over the ranges tested. Halving the stem density from $N = 50$ to $N = 25$ stems m^{-2} costs 9 percentage points of band-averaged attenuation (24% to 15%), whereas reducing the root and trunk drag coefficient by more than half, from $C_d = 3.5$ to $C_d = 1.5$, costs only 7 points (24% to 17%), and 6 of those 7 points are lost between $C_d = 3.5$ and $C_d = 2.0$. The response to C_d is therefore markedly sub-linear, even though the vegetation force is linear in C_d in Eq. 4. A plausible explanation lies in the feedback embedded in the drag term itself: because the force scales with $|u|$, stronger dissipation lowers the orbital velocity further into the forest, so each additional increment of C_d acts on a progressively weaker flow and returns progressively less. The practical implication is that once C_d exceeds roughly 2, further increases buy little additional protection, whereas stem density continues to pay across the whole range examined. For restoration design this ranks planting density above species-specific root-drag characteristics as the lever with the larger and more predictable return — a conclusion that follows from the controlled numerical campaign and could not be drawn from any single physical experiment.

Expressed in engineering terms, the high-density forest gives a through-forest transmission coefficient of $K_t = H_{m0}(52)/H_{m0}(35) = 0.45$ across a 17 m band: fewer than half of the incident wave height at the seaward edge survives to the landward edge. This is the form in which coastal structures are normally specified, and it invites direct comparison with the engineered wave-dissipating structures studied under Indonesian conditions [31], with the difference that the same order of performance is obtained without a hard structure and with the ecological co-benefits of the forest itself [21], [33]. The spectra in Figure 7 further show that the decay is not spectrally uniform, which matters in practice because it is the residual energy, and not the residual height alone, that sets the design condition for any asset landward of the forest.

Relative to the benchmark, the novelty is not the agreement itself (24% against a reported 13–28% for high density, and 15% against approximately 16% for low density; Table 4) but what the agreement licenses. Once an open-source, wave-resolving model reproduces

a prototype-scale experiment at the aggregate level, the same configuration can be re-run at negligible cost for combinations that the flume cannot afford. The 9-point high-versus-low density difference obtained here, against 12% in the physical model [14], is a case in point: the numerical campaign isolates that difference with the bathymetry, the forcing and every other vegetation property held exactly constant, whereas the physical model necessarily altered the individual placement of trees between configurations. The residual 3-point discrepancy is therefore informative rather than merely a source of error, and is consistent with the ordered stem arrangement of the model against the random arrangement of the flume — a systematic, not a random, difference.

Two qualifications bound these claims. The agreement is aggregate rather than gauge-by-gauge, for the reasons set out in Section IV.D, and the imposed relative wave height exceeds the non-breaking range of the benchmark, so depth-induced breaking contributes to the total decay. Because every reduction quoted here is differenced against the no-vegetation run, which carries the same breaking and bed friction, the vegetation-attributable component is still isolated; the absolute transmission coefficient reported above, however, is specific to this forcing and should not be transferred to non-breaking conditions without re-running the model.

1) *Scaling of the mangrove environment*

The present study is purely numerical and has no geometric scale: the domain, water depth, wave forcing and vegetation dimensions are specified directly at the prototype scale of Kelty et al. [14]. The free-surface wave dynamics, governed by Froude similarity in the non-hydrostatic shallow-water equations, are therefore reproduced without scale distortion, and the Froude–Reynolds conflict that constrains physical models does not arise. The Reynolds dependence enters only through the bulk drag coefficient C_d , which is a prescribed, layer-specific input; because the model reproduces the prototype-scale geometry and flow of Kelty et al. [14], the adopted C_d values correspond to the same Reynolds regime as their Reynolds-scaled physical model.

2) *Ecological representation of the mangrove*

In coastal-engineering practice, wave–vegetation models such as XBeach represent vegetation through physical flow-resistance parameters (per layer: stem diameter b_v , element density N , layer height h_v , and bulk drag coefficient C_d) rather than ecological descriptors. Ecological metrics such as diameter at breast height, basal area, tree density (trees ha^{-1}) and biomass characterise the stand for ecological purposes but do not enter the hydrodynamic equations directly; translating them is non-trivial because a *Rhizophora* tree comprises a prop-root network, trunk and canopy that must be schematised as separate layers, and the hydrodynamic element density (per m^2) far exceeds the ecological tree density (per-ha). The model is therefore parameterised physically (Table 2), with this conversion treated as a modelling assumption.

3) *Limitations and future work*

The drag coefficients explored here ($C_d = 1.5\text{--}3.5$) span a bounded range; a wider, species- and flow-

specific parametric sweep of C_d is an important avenue for future work, as is resolving the variation of C_d with the Reynolds-dependent intra-wave velocity rather than prescribing a constant bulk value per layer. As a numerical study validated against a prototype-scale physical model, the present results also require validation under real, irregular, multi-directional field wave climates before operational use in coastal management.

V. CONCLUSION

This study set out to meet the three objectives stated in the abstract: to quantify wave attenuation across a mangrove band at its seaward edge ($x = 35$ m), its middle ($x = 44$ m) and its landward edge ($x = 52$ m); to isolate the independent effects of vegetation density and of the layer-resolved drag coefficient; and to assess the consistency of an open-source, wave-resolving model against a prototype-scale physical benchmark. Each is addressed in turn.

On the first objective, the significant wave height in the high-density forest decayed monotonically along the band, from $H_{m0} = 0.59$ m at $x = 35$ m to 0.38 m at $x = 44$ m and 0.26 m at $x = 52$ m. This corresponds to a through-forest transmission coefficient of $K_t = 0.45$ across the 17 m band and a band-averaged reduction of 24% relative to the unvegetated baseline.

On the second objective, vegetation density proved to be the dominant control. Halving the stem density from 50 to 25 stems m^{-2} lowered the band-averaged reduction from 24% to 15%, an almost proportional response, whereas reducing the root and trunk drag coefficient from 3.5 to 2.0 and then to 1.5 lowered it only to 18% and 17% respectively. The dependence on C_d is monotonic but sub-linear and saturates above $C_d \approx 2$. For restoration design, planting density is therefore a more reliable lever than species-specific root drag.

On the third objective, the model is consistent with the prototype-scale experiment of Kelty et al. [14] at the aggregate level: 24% against a reported 13–28% for high density, 15% against approximately 16% for low density, and a high-to-low density difference of 9% against 12%. The consistency is aggregate rather than gauge-by-gauge, and the imposed relative wave height exceeds the non-breaking range of the benchmark, so the agreement should be read as indicative rather than as a strict reproduction of the benchmark's hydrodynamic regime.

The wider implication is that a wave-resolving, layer-schematised vegetation model, once checked at prototype scale, provides an inexpensive and transferable framework for exploring mangrove configurations that are impractical to reproduce physically, and thereby supports the quantitative design of nature-based coastal defences. Future work should extend the C_d sweep to species- and flow-specific values, resolve the intra-wave variation of C_d rather than prescribing a constant bulk value per layer, reproduce a specific non-breaking case of the benchmark, and validate the framework under real, irregular, multi-directional field wave climates before operational use in coastal management.

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