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Full Length Article

Role of Mangrove Forests in Coastal Protection: An Analytical Study of the Sundarbans as a Natural Barrier against Cyclones, Erosion, and Sea-Level Rise

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Abstract

Background: *The Indian Sundarbans faces threats from tropical cyclones, storm surges, channel migration, coastal erosion, rising relative sea levels, and frequent embankment collapses. Mangrove ecosystems may mitigate some aspects of this risk; nevertheless, their protective efficacy is contingent upon factors such as forest breadth, plant architecture, landform characteristics, water depth, sediment availability, and the severity of hazards. Methods: This analytical secondary-data investigation amalgamated official cyclone documentation for Amphan, Yaas, and Remal; evaluations from the Forest Survey of India; a remote-sensing dataset spanning 2000-2020 for biosphere-reserve areas and coastal islands; a comprehensive water-level analysis across the delta; and scholarly research on the flood-mitigating effects of mangroves. Descriptive statistics, absolute and percentage variations, compound rates, Pearson and Spearman correlations, and simple linear regression were used just in the presence of similar data. Findings: The chosen cyclones had an average sustained wind speed of 136.7 km/h and an average recorded gust of 158.3 km/h. Amphan traversed the West Bengal-Bangladesh coastline via the Sundarbans, with sustained winds of 155-165 km/h and gusts reaching 185 km/h; the official post-event report documented a tidal wave or surge height of around 4.6 m in the impacted coastal regions. Nine uncovered mangrove islands saw a reduction of 48.6 km² from 2000 to 2020, averaging a loss of 5.40 km² and a percentage decline of 18.6%. The initial island area exhibited a positive albeit non-significant correlation with absolute loss (Pearson r=0.58, p=0.101). Core and buffer mangroves diminished, and plantations in the transition zone proliferated. Conclusion: Mangroves need to be seen as a risk-mitigating layer instead of an impenetrable barrier. Successful policy necessitates the safeguarding of extensive natural corridors, restoration sensitive to sediment and hydrology, provision for landward migration, robust embankments and shelters, settlement planning based on hazards, and monitoring that correlates vegetation health with observed waves, water levels, erosion, and damage.*

Keywords: *Sundarbans; mangrove attenuation; cyclone risk; coastal erosion; relative sea-level rise; nature-based solutions; hybrid protection*

1. Introduction

Coastal defence in the Sundarbans is often characterized by the analogy of a natural barrier. The analogy is beneficial since mangrove trunks, limbs, foliage, prop roots, pneumatophores, and uneven forest ground provide resistance against flowing water and wind-induced waves. It is likewise insufficient. A wall has a static top, a defined material resilience, and a dichotomous failure condition; a mangrove ecosystem is dynamic, spatially varied, influenced by tides, and able to develop, sustain damage, recover, and migrate inland. Its safeguarding role is therefore contingent rather than unequivocal. The primary inquiry is not if mangroves mitigate cyclones, but rather which elements of hazard they can diminish, at what ranges, under which ecological and geomorphic circumstances, and how this attenuation should be harmonized with engineered and societal safeguards (Menéndez et al., 2020; van Hespen et al., 2023; Lovelock, 2024).

The Indian Sundarbans is situated at the coastal edge of the Ganges-Brahmaputra-Meghna delta. Tidal canals fragment safeguarded mangrove islands and populated, fortified islands; low-lying areas are occupied by towns, agriculture, aquaculture ponds, roads, jetties, and tourist amenities; access to mainland services is limited by rivers and climatic conditions. Exposure is inconsistent. Islands next to the sea have direct impacts from waves and surges, riverbanks are influenced by tidal flows and boat wakes, and isolated communities may stay inundated after a breach in their embankments. Consequently, the same cyclone might result in canopy destruction in protected forests, salty inundation in agricultural areas, pollution of potable water, loss of dwellings, and extended disruptions to revenue across various locations (IPCC, 2022; World Bank, 2021).

Three recent intense cyclones delineate current hazards. Super Cyclonic Storm Amphan swept the West Bengal-Bangladesh coastline via the Sundarbans on May 20, 2020. Extremely Intense Cyclonic Storm Yaas struck the northern Odisha coastline on 26 May 2021, causing elevated water levels, surge-induced floods, and embankment effects in many regions of coastal West Bengal. The intense Cyclonic Storm Remal made landfall on the coast of Bangladesh and neighbouring West Bengal on 26-27 May 2024, between Sagar Island and Khepupara. These occurrences vary in terms of trajectory, severity, tidal stage, precipitation, prior circumstances, and reporting mechanisms, so their damage assessments cannot be regarded as controlled trials (India Meteorological Department, 2020, 2021, 2025). The National Disaster Response Force (2021) and Kumar et al. (2021) also record aspects related to disaster response and post-event scenarios.

This study assesses the Sundarbans as a natural defence while not ascribing all variations in harm to plant life. It distinguishes between danger, exposure, vulnerability, and ecosystem status; maintains a clear separation of Indian and transboundary data; and uses changes in mangrove areas on vulnerable islands as an indication of erosion-related habitat rather than a direct assessment of coastline location. The objective is to discern robust quantitative indicators, clarify the limitations of the existing data, and suggest a multifaceted coastal protection approach that integrates mangroves, sediment, embankments, shelters, warning systems, land-use regulations, and livelihood resilience as synergistic components.

2. Context of the Study and Issue Identification

The danger of cyclones arises from interrelated factors. Atmospheric pressure and wind generate waves and storm surges; astronomical tides alter the water-level baseline; river flow and precipitation increase volume; bathymetry, channel configuration, and coastline alignment dictate propagation; and local elevation determines inundation depth. The extent of damage is contingent upon the site and condition of structures, levees, transportation, freshwater reserves, agricultural produce, animals, evacuation pathways, and domestic possessions. Mangroves function in this system by modifying flow resistance, dissipating waves, stabilising sediments, and diminishing certain wind exposure; yet, they are incapable of eliminating severe regional water-level irregularities or safeguarding assets situated in all low-lying areas (Krauss &Osland, 2020; van Hespen et al., 2023).

The issue of policy is exacerbated by environmental changes. A protective belt may diminish due to persistent erosion, become disjointed, or transition into brief and sparse flora. A plantation may expand the designated forest area but may still be too immature, narrow, inadequately linked to tidal flows, or improperly located to provide the same benefits as an established natural forest. On the other hand, robust mangroves may be diminished when rigid constructions alter water flows or remove habitat areas. Cumulative canopy-area data are therefore inadequate for coastal engineering determinations. The parameters of width, frontal exposure, stem density, root complexity, elevation, sedimentation, species composition, and continuity should be collectively monitored (Forest Survey of India, 2021, 2024; Bryan-Brown et al., 2020; Worthington et al., 2020).

The issue is dynamic due to sea-level rise and subsidence. Delta water levels indicate alterations in global ocean dynamics, vertical land displacement, fluctuations in freshwater availability, and regional hydrodynamic conditions. Becker et al. (2020) analysed fluctuations in water levels at 101 gauges across the broader delta and calculated an average increase of around 3 mm annually since the 1970s, which is somewhat quicker than the current world average. This is a delta-wide contextual approximation, rather than a localised Sundarbans tide-gauge measurement. For specific islands, the relevant measure is the proportionate increase in sea level juxtaposed with surface elevation growth and the equilibrium of coastal sediment. When elevation rise fails to match, the stress from mangrove floods, erosion, and vulnerability to settlement intensifies.

3. Review of Literature

Theoretical physics posits that plant life diminishes wave energy via drag and turbulence. The extent of decrease is contingent upon the water depth in relation to plant height, as well as stem and root density, vegetation pliability, wave duration, forest breadth, and the existence of channels. Attenuation is often most pronounced for brief wind waves across thick vegetation and less effective for prolonged storm surges, which may influence water levels throughout an extensive coastal area. Even with a little decrease in surge height, diminished currents and decreased wave activity may mitigate structural stress and erosion. These differences explain the significant variability in assessed advantages and the inappropriateness of applying a uniform percentage decrease across different coasts (Menéndez et al., 2020; van Hespen et al., 2023).

Menéndez et al. (2020) shown via global modelling that mangroves provide significant flood protection advantages by decreasing anticipated yearly damages; nonetheless, the global outcome lacks a site-specific design coefficient. Local applications need topographical features, plant types, water levels, wave conditions, and asset vulnerability. The analysis conducted by van Hespen et al. (2023) likewise underscored that nature-inspired flood defence should include biological limits and unpredictability. Mangroves may adjust by capturing sediment and increasing in height, but they may struggle when erosion occurs too fast, silt is lacking, or landward movement is obstructed. Coastal preservation strategies must thus safeguard the mechanisms that support the forest, rather than only the existing trees.

Cyclone ecology adds an additional dimension. Krauss and Osland (2020) elucidated the manner in which cyclone winds, waves, salinity, and sediment deposition alter mangrove architecture. Harm may include leaf loss, stem fracture, uprooting, entombment, soil erosion, and extended physiological strain. Restoration is contingent upon species characteristics, pre-storm status, availability of propagules, hydrological reestablishment, and the occurrence of further storms. Amaral et al. (2023) shown that both event intensity and landscape context govern vulnerability and resilience. A forest subjected to frequent disturbances prior to canopy regeneration may forfeit its protective framework, despite the delineation of its boundaries being constant. This analysis aligns with worldwide evaluations that associate protective capability with forest health, fragmentation, climate-induced degradation, and the risk of ecosystem collapse (Food and Agriculture Organization of the United Nations, 2020; Global Mangrove Alliance, 2024; Goldberg et al., 2020; Sievers et al., 2020).

Remote observation of the Indian Sundarbans corroborates this apprehension. Samanta et al. (2021) documented a reduction of 58.0 km² in core mangroves and a 51.8 km² decrease in buffer mangroves between 2000 and 2020, with an increase of 81.2 km² in the transition zone. The overall mapped region decreased by 28.7 km²; however, the internal reallocation is more significant for coastal safeguarding: losses transpired from adjacent reserve forests, including islands facing the sea, while gains were mostly found in anthropogenically altered transitional zones. Vegetation-index assessments also revealed extensive adverse health patterns. Consequently, a little area net alteration may obscure diminished safeguarding at the most vulnerable perimeter.

The historical context of shorelines affects future susceptibility. Bhargava and Friess (2022) discovered that previous dynamics influence the stability, retreat, or advancement of a mangrove coastline. This aligns with the findings from the Sundarbans islands: some shorelines experience erosion while protected banks accumulate, and a single island may exhibit both phenomena. Restoration efforts performed on a dynamically eroding bank without considering hydrodynamic factors are prone to failure. In contrast, aided natural regeneration in a depositional intertidal environment may cultivate resilient plants at a reduced planting expense. Site selection should thus start with erosion-accretion patterns and sediment allocations instead of bureaucratic planting objectives.

The nascent literature on nature-based solutions dismisses the erroneous dichotomy between mangroves and engineering. Embankments may safeguard communities from regular tidal events; nevertheless, they may also sever floodplains from sediment, resulting in disastrous outcomes when compromised. Mangroves may mitigate wave pressure on a levee, but set-back or strategically redesigned levees can provide room for intertidal flora and sediment accumulation. Shelters, alerts, evacuation transportation, enhanced water systems, and durable housing mitigate residual risks that no ecological safeguard can eliminate. The suitable model is both hybrid and adaptable, with performance assessed post-storms and modified as coastlines and communities evolve (IPCC, 2022; UNEP, 2023; Lovelock, 2024).

4. Research Deficiency, Purpose, Goals, and Enquiries

Public discourse often attributes the protection of Kolkata and coastal areas to the Sundarbans; however, contemporary Indian data lacks a systematic comparison of similar locations with and without mangroves during the same storm. Damage assessments use varying spatial delineations, and vegetation measurements are seldom associated with recorded wave or flood data. A meticulous secondary-data analysis must hence refrain from a causal damage-reduction coefficient that lacks evidential backing. The study gap constitutes a comprehensive evaluation that links official cyclone intensity, documented habitat alterations, erosion-induced island disappearance, water-level circumstances, and the scenarios in which mangroves might provide protective benefits.

The research sought to: (1) elucidate the processes through which mangroves mitigate waves, currents, erosion, and certain wind impacts; (2) analyse the official intensity metrics of Amphan, Yaas, and Remal; (3) measure the loss of mangrove areas on vulnerable islands and within biosphere-reserve zones; (4) evaluate the consequences of relative water-level elevation and sediment behaviour; and (5) formulate a hybrid management approach. The primary enquiries were whether the protective habitat is altering at the exposed edge, if bigger sea-facing islands have had more significant absolute loss, and which governance metrics may facilitate future research in linking vegetation health with hazard mitigation and damage prevention.

5. Methods and Materials

The research used a convergent secondary-data methodology. Quantitative data was organised into distinct sheets for cyclone intensity, mangrove coverage per reserve zone, size of sea-facing islands, state-level mangrove coverage, and delta water-level conditions. Qualitative data was categorised into four themes: attenuation mechanism, ecological situation, engineering interaction, and institutional reaction. The main research region was the Indian Sundarbans located in West Bengal. Information from Bangladesh was used just when an official cyclone trajectory or landfall intersected the international coastal zone; data on forest and damage in Bangladesh were not amalgamated with Indian statistics.

Investigations included publications and government reports from 2020 to 2025, retaining earlier materials just where they provided essential baseline or methodological context. Search keywords combined Sundarbans or Indian Sundarbans with mangrove, cyclone, storm surge, wave mitigation, erosion, coastline, sea elevation, subsidence, levee, Amphan, Yaas, Remal, rehabilitation, and nature-centric solution. Sources were included when their location, date, variable, and measurement unit were ascertainable. News articles, unidentified websites, unverified assertions, and replicated data were omitted.

Cyclone strength measurements were sourced from reports by the India Meteorological Department. The sustained wind speeds were indicated by the averages of the official landfall ranges: 160 km/h for Amphan, 135 km/h for Yaas, and 115 km/h for Remal. The highest recorded wind gusts were 185, 155, and 135 km/h. The midpoint transformation was used only for descriptive analysis and is clearly reported in the data table. It fails to translate winds particular to each track into a standardised local wind measurement applicable to all islands in the Sundarbans.

Observations pertaining to mangrove regions were derived from Samanta et al. (2021). Core, buffer, transition, and overall regions were delineated for the years 2000, 2005, 2010, 2015, and 2020. For nine coastal islands, mangrove areas from 2000 and 2020 were used to compute absolute loss, proportionate loss, mean, median, sample standard deviation, and range. No missing values were estimated. Observations from the State-level Forest Survey were preserved as contextual evidence but not integrated with the remote-sensing dataset due to variations in borders, sensors, and categorisation criteria.

The relationship between the baseline area of islands and total loss was assessed using Pearson correlation, Spearman rank correlation, and basic ordinary least squares regression. These examinations enquire whether bigger islands generally had greater losses in square kilometres, rather than investigating if size induced erosion. The limited number of nine islands results in less statistical power, and the findings may be influenced by geographical factors; hence, the p-values are just exploratory. The regression analysis presents the slope and R-squared values, however the commentary emphasises impact direction, scatter, and geomorphic plausibility more than a binary significant level.

Cyclone wind parameters were encapsulated via mean, median, minimum, maximum, range, and sample standard deviation. Inferential testing was not conducted since the three chosen occurrences do neither provide a random sample of all storms nor independent repetitions of a single exposure condition. The Amphan surge, quantified at around 4.6 meters, was maintained as event-specific official data; no standardised surge measurements were allocated to Yaas or Remal due to the absence of directly comparable values from the Sundarbans in the chosen reports.

The examination was performed in Python using pandas, NumPy, SciPy, and Matplotlib. All equations were replicable: the percentage change was calculated as $100 \times (\text{final} - \text{initial})/\text{initial}$; the compound annual growth rate was determined using $100 \times [(\text{final}/\text{initial})^{(1/\text{years})} - 1]$; and the total island loss was defined as the area in 2000 subtracted from the area in 2020. The results were rounded only for display purposes. The design is unable to assess mitigated damages or a causal attenuation coefficient due to the unavailability of matching wave gauges, topographic exposure data, forest structure information, and asset-loss observations.

6. Study-Area Overview

The research region encompasses the Indian Sundarbans in South 24 Parganas and the neighbouring deltaic region of West Bengal, with safeguarded mangrove islands, the Sundarban Tiger Reserve, Biosphere Reserve areas, populated embanked islands, tidal channels, and the coastal access point of Sagar Island. The Bangladesh region is used only in instances when a cyclone's landing narrative must include the international coastline. Forest regions, hydrological measurements, and event repercussions are not compiled over the boundary. The terrain is flat, characterised by monsoonal weather, significant tidal variations, sedimentary deposits, and extensive fragmentation, with access and emergency services reliant on ferries, boats, embankments, and a constrained road system. The Sundarban Tiger Reserve's designation as a reserve, World Heritage site, biosphere reserve, and Ramsar site is substantiated by the Sundarban Tiger Reserve (2025), UNESCO World Heritage Centre (2025), UNESCO Man and the Biosphere Programme (2025), and Ramsar Sites Information Service (2025).

7. Results

Table 1. Coastal-protection services provided by mangroves and limits of inference

Service	Primary mechanism	Expected spatial scale	Principal limitation
Wind-wave attenuation	Vegetation drag, turbulence and wave breaking	Within and immediately landward of forest belt	Varies with depth, wave period, width, density and gaps
Current reduction	Root and stem friction	Creeks, intertidal platforms and flood pathways	Channels can bypass vegetation; extreme flow can damage trees
Storm-surge moderation	Added friction and storage across wide landscapes	Landscape scale when forest is sufficiently extensive	Regional water-level anomaly persists; effect is event-specific
Shoreline stabilisation	Root reinforcement, sediment trapping and organic accretion	Bank and platform scale	Fails under severe scour or sediment deficit
Wind exposure reduction	Canopy and stem drag	Within/behind local forest edge	Does not change cyclone-scale wind field
Embankment load reduction	Lower incident waves and current velocity	Mangrove-embankment system	Requires intact foreshore and maintenance

Sources: Menéndez et al. (2020), Krauss and Osland (2020), van Hespen et al. (2023), and Lovelock (2024).

Table 1 separates the major protective services. Wave attenuation and current reduction have the most direct short-distance physical mechanism; surge reduction is more conditional because regional water levels can remain high even when waves are damped. Sediment trapping and root reinforcement can stabilise suitable banks, but active channel scour may overwhelm vegetation. Canopy drag can reduce near-surface wind within and immediately behind a forest, whereas cyclone-scale wind fields remain unaffected. These distinctions prevent the broad term coastal protection from becoming an untestable claim.

Table 2. Selected severe cyclone events affecting the Indian Sundarbans region

Event	Year	Landfall context	Sustained wind (km/h)	Gust (km/h)	Water-level/surge note
Amphan	2020	West Bengal-Bangladesh coast across the Sundarbans	160 midpoint	185	Approx. 4.6 m realised tidal wave/surge in affected coastal sector
Yaas	2021	North Odisha coast; major surge and embankment impacts in the Indian Sundarbans	135 midpoint	155	No harmonised Sundarbans value used
Remal	2024	Bangladesh and adjoining West Bengal between Sagar Island and Khepupara	115 midpoint	135	No harmonised Sundarbans value used

Sources: IMD (2020, 2021, 2025). Wind midpoints are author-derived from official ranges; surge values were not standardised across events.

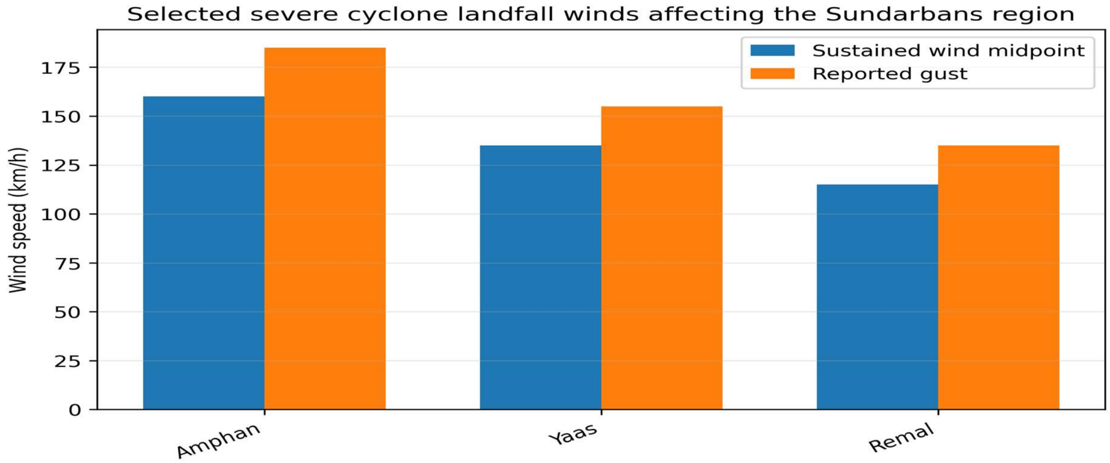

Figure 1. Selected severe cyclone landfall winds affecting the Sundarbans region

Source: Author chart from IMD (2020, 2021, 2025). Values are landfall descriptors, not island-specific anemometer readings.

The selected cyclone comparison in Table 2 and Figure 1 shows a declining sequence of official landfall wind midpoints from Amphan to Yaas to Remal, but this must not be interpreted as a damage ranking for the Indian Sundarbans. Amphan's sustained range of 155-165 km/h and gust to 185 km/h accompanied a landfall across the Sundarbans coast. Yaas was centred farther west in Odisha yet produced serious high-water impacts in West Bengal. Remal crossed the Bangladesh-adjoining West Bengal sector with lower reported landfall winds but substantial rainfall and coastal disruption. Track, tide, exposure, and asset vulnerability differ.

Across the three events, the mean sustained-wind midpoint was 136.67 km/h, the median was 135.00 km/h, and the sample standard deviation was 22.55 km/h. Mean peak gust was 158.33 km/h, with a median of 155.00 km/h and sample standard deviation of 25.17 km/h. The three-event sample is descriptive only; it does not justify a probability model or hypothesis test.

Table 3. Descriptive statistics for selected cyclone landfall wind indicators

Indicator	n	Mean	Median	Minimum	Maximum	Sample SD
Sustained-wind midpoint (km/h)	3	136.67	135.00	115	160	22.55
Reported gust (km/h)	3	158.33	155.00	135	185	25.17

Source: Author calculations from IMD event reports. No inferential testing was conducted because these are three purposively selected, non-comparable events.

Table 4. Mangrove-area trajectories by Sundarbans Biosphere Reserve zone, 2000-2020

Zone	2000 (km²)	2020 (km²)	Change (km²)	Change (%)
Core	903.2	845.2	-58.0	-6.42
Buffer	1084.7	1032.9	-51.8	-4.78
Transition	86.2	167.4	+81.2	+94.20
Total	2074.1	2045.4	-28.7	-1.38

Source: Samanta et al. (2021); author calculations. Transition gain equalled 74.0% of combined core-buffer loss by area.

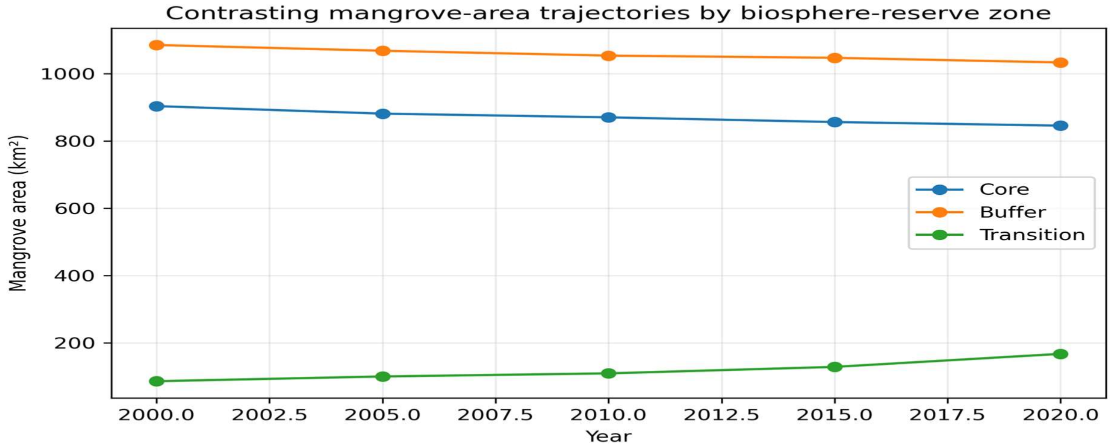

Figure 2. Contrasting mangrove-area trajectories by biosphere-reserve zone

Source: Author chart from Samanta et al. (2021). Area trajectory is an exposure-context indicator, not a direct wave-attenuation measurement.

The reserve-zone series in Table 4 indicates contrasting trajectories. Core mangroves fell from 903.2 to 845.2 km² and buffer mangroves from 1,084.7 to 1,032.9 km² between 2000 and 2020. Transition-zone mangroves rose from 86.2 to 167.4 km². The combined 81.2 km² transition gain was smaller than the 109.8 km² loss from core and buffer, replacing 74.0% of that loss by area. More importantly, the gain occurred in a different protection and exposure context, so it cannot be assumed to replace seaward risk-reduction services.

Table 5. Mangrove-area change on nine sea-facing islands, 2000-2020

Island	2000 (km²)	2020 (km²)	Loss (km²)	Loss (%)
Jammudwip	3.9	2.6	1.3	33.3
Dhanchi	32.1	28.0	4.1	12.8
Bulcherry	22.1	17.2	4.9	22.2
Chulkati	38.5	32.9	5.6	14.5
Dalhousie	63.0	51.4	11.6	18.4
Bhangaduni	30.0	19.1	10.9	36.3
Mechua	18.3	15.7	2.6	14.2
Chamta	37.0	34.0	3.0	8.1
Baghmara	58.2	53.6	4.6	7.9

Source: Samanta et al. (2021); author calculations. Total loss=48.6 km²; mean loss=5.40 km²; sample SD=3.57 km².

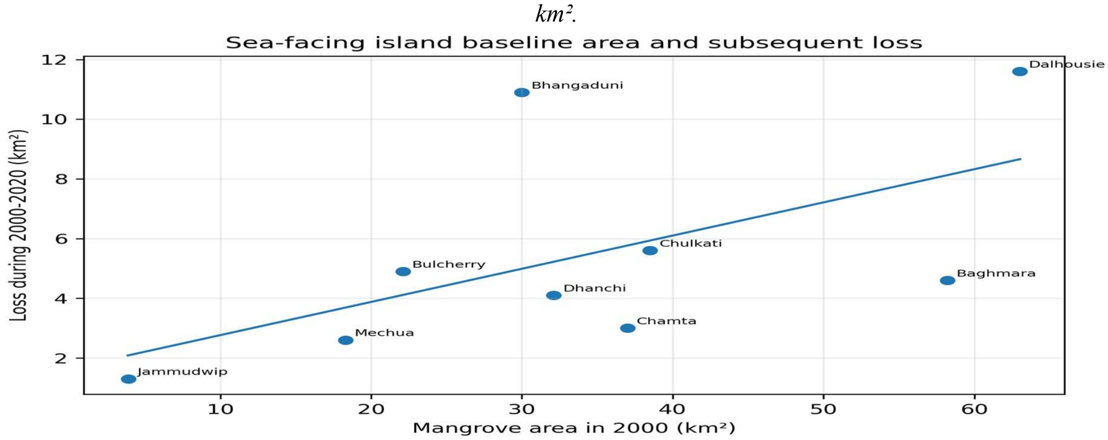

Figure 3. Sea-facing island baseline mangrove area and subsequent loss

Source: Author analysis of Samanta et al. (2021). Regression is exploratory (n=9).

All nine extracted sea-facing islands lost mangrove area between 2000 and 2020. Total loss was 48.6 km²; mean loss was 5.40 km²; median loss was 4.60 km²; sample standard deviation was 3.57 km²; and the range was 1.3-11.6 km². Mean proportional loss was 18.64%. Bhangaduni lost the largest share, while Dalhousie lost the largest absolute area in the extracted series.

Figure 3 tests whether larger initial islands lost more area. Pearson correlation was r=0.580 (n=9, p=0.101); Spearman rank correlation was rho=0.633 (p=0.067). The regression slope was 0.111 km² of loss per additional baseline km², with R^2=0.337. Effect directions were positive but uncertainty was large, so the result is best read as exploratory evidence that baseline area alone does not explain shoreline-related loss.

Table 6. Sea-level, erosion, and mangrove-condition indicators relevant to protection

Indicator	Spatial/temporal basis	Reported or derived signal	Use in this study
Delta water-level change	101 gauges, wider GBM delta since 1970s	Approximately 3 mm/year average rise	Regional context only; not a local Sundarbans rate
Sea-facing island mangrove area	Nine Indian islands, 2000-2020	All declined; 48.6 km² total loss	Erosion-related habitat exposure indicator
Core and buffer mangrove area	Indian SBR, 2000-2020	Combined decline of 109.8 km²	Loss of contiguous protected forest
Transition-zone mangrove area	Indian SBR, 2000-2020	Increase of 81.2 km²	Restoration/regeneration context, not functional equivalence
Vegetation health	Landsat and MODIS indices, 2000-2020	Predominantly negative trends in many pixels	Potential decline in structural condition
State mangrove cover	West Bengal FSI assessments	Small net increase over selected years	Administrative canopy-area context

Sources: Becker et al. (2020), Samanta et al. (2021), and FSI (2021, 2024). Indicators use different spatial definitions and were not pooled.

Table 5 distinguishes water-level and erosion indicators by scale. The approximately 3 mm/year delta-wide water-level rise reconstructed by Becker et al. (2020) provides regional context, while the island losses provide local exposure evidence. Neither is a direct measure of inundation depth at a specific settlement. A valid local risk model would require vertical land motion, tidal datum, surge, wave, elevation, and embankment data in the same coordinate system.

Table 7. Mangrove condition, expected protection outcome, and management response

Condition	Expected protective performance	Failure pathway	Management response
Wide, mature, connected natural belt	Highest relative wave/current attenuation and sediment function	Severe surge, channel bypass, frontal erosion	Strict protection; maintain hydrology and migration space
Narrow or fragmented belt	Reduced roughness path and possible bypass	Gaps concentrate flow and waves	Gap repair, width targets, remove avoidable fragmentation
Young plantation	Low initial roughness; benefits grow with structure	Mortality, wrong elevation/species, storm damage	Hydrology-first design; multi-year outcome contracts
Scouring shoreline	Low establishment probability	Erosion exceeds root and sediment response	Diagnose hydrodynamics; use selective wave reduction or retreat

Condition	Expected protective performance	Failure pathway	Management response
Mangrove plus maintained embankment	Complementary reduction of loading and overtopping risk	Poor maintenance or loss of foreshore	Joint asset management and post-storm inspection
Mangrove with shelters and warnings	Reduces physical energy while social systems reduce mortality	Warning or evacuation failure	Redundant communication and accessible shelters

Source: Author synthesis from Menéndez et al. (2020), van Hespen et al. (2023), IPCC (2022), and MoEFCC (2021, 2022, 2023, 2024, 2025).

Table 6 translates vegetation condition into expected protection outcomes. Wide, structurally complex natural forest has the strongest theoretical attenuation potential; narrow or fragmented belts allow waves and flows to bypass vegetation; young plantations provide limited initial roughness and require time to develop; and hydrologically disconnected planting can fail despite high seedling counts. The table therefore treats forest width and condition as performance variables rather than assuming that all mapped mangrove hectares deliver equal service.

The strategy matrix in Table 7 prioritises risk reduction by combining ecological and engineered measures. Protection of existing exposed forest is immediate and avoids the long lag before restoration becomes functional. Hydrology-first restoration and accommodation space address ecological persistence. Embankment maintenance, shelters, warnings, and freshwater protection address residual risk. Instrumented monitoring supplies the evidence needed to revise designs after future storms.

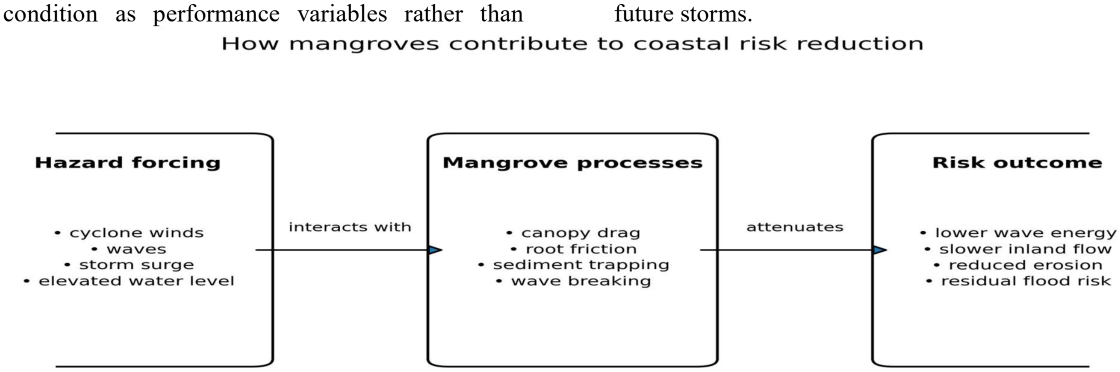

Figure 4. How mangroves contribute to coastal risk reduction

Source: Author-developed conceptual synthesis. The final box explicitly retains residual flood risk.

Figure 4 encapsulates the causal framework: cyclone winds, waves, storm surge, and heightened water levels engage with mangrove roughness and sediment dynamics; this engagement may diminish wave energy, decelerate inland flow, and stabilise some shorelines, although it does not eliminate residual flooding. The framework intentionally concludes with residual risk, since any management approach that portrays mangroves as offering total protection would promote hazardous settlement and insufficient investment in readiness.

8. Discourse

The examination supports a conditional natural-barrier interpretation. Mangroves may diminish wave height, flow velocity, near-bank erosion, and some wind forces; nevertheless, their impact is neither consistently distributed nor enough to counteract a significant cyclone. The severity of Amphan and elevated coastal water levels illustrate the disparity between the resistance of local vegetation and the pressure of regional surges. Simultaneously, a forested area that diminishes wave intensity before to their arrival at a barrier might significantly decrease the likelihood of breaching, even if it does not entirely avert flooding in all locations. The relevant effect of the strategy is a reduced risk of energy hazards and damage likelihood, rather than an absolute elimination of water.

The most significant local alert is to the depletion of the coastal woodland. The nine-island sample saw a reduction of 48.6 km² of mangrove territory during a span of twenty years, with each island in the analysed group showing a decrease. Core and buffer zones diminished, but the transition-zone area increased. From the standpoint of coastal preservation, geographical positioning is more significant than mere numerical substitution: one hectare situated behind a barrier or inside a protected inlet does not equivalently replace one hectare taken from an expansive exposed area. Accounting systems need to categorise profits and losses based on wave exposure, forest breadth, elevation, age, connection, and potential benefits to particular communities or infrastructure.

The favourable correlation between beginning island size and total loss is expected, since bigger islands possess more area to potentially lose, however its ambiguity provides valuable insights. The Pearson r exhibited a modest and non-significant value at the traditional 0.05 threshold, with the rank correlation reflecting a similar pattern. Erosion is clearly not only a function of initial area. Orientation, tidal-channel movement, sediment availability, coastal history, plant composition, and cyclone vulnerability probably account for a significant portion of the residual variance. Subsequent investigations have to include coastal transects, annual rates in meters, and multilevel models instead of considering island totals as uniform entities.

The elevation of relative sea levels enhances the significance of sediment management. If water levels increase and embanked areas accumulate little fresh silt, the height disparity between communities and nearby tidal waters expands. Mangroves have the capacity to gather sediment under conditions when hydroperiod and supply are favourable, although they are incapable of generating sediment that is not provided or enduring perpetual flooding. Protection initiatives have to assess changes in surface elevation, suspended sediment levels, stream interconnectivity, and tidal fluctuations. A planting objective without an elevation budget might provide ephemeral flora and misguided assurance.

The recovery from cyclones is another overlooked aspect of performance. A mangrove strip may safeguard a levee during one occurrence, although it might be left barren or compromised when the subsequent event occurs. Focusing just on the area may overlook decreases in canopy density, stem robustness, and understorey intricacy. Post-storm assessments need to measure mortality, damage, erosion, silt accumulation, regrowth, and the duration for functional recovery. In areas prone to recurrent cyclones throughout the recovery phase, restoration efforts have to include a variety of species and age classes instead of establishing uniform-aged monocultures susceptible to shared failure mechanisms.

Hybrid protection is not only a trade-off; it contains many risk strategies. Mangroves excel in attenuating waves and currents while stabilising appropriate intertidal deposits. Embankments provide a certain height barrier but need upkeep and may collapse suddenly. Shelters and alerts diminish fatalities, increased water storage safeguards health, insurance and social safety nets expedite recovery, and land-use regulations avert new risks. These actions need to be structured as a cohesive system. An embankment positioned behind a rehabilitated intertidal platform may endure reduced wave forces and facilitate the migration of the mangrove belt.

The examination also has distributive consequences. Coastal defences that favour lucrative tourists or infrastructure, while neglecting resource-dependent communities, may exacerbate inequality. Limitations on mangroves could incur immediate access costs for fishermen and gatherers, notwithstanding the regional advantages of conservation. Equitable execution requires clear zoning, compensation for lost access, funded restoration and oversight responsibilities, and involvement from women, fishermen, farmers, boat operators, and homes on the forest periphery. Nature-based solutions are sustainable just when the communities tasked with their upkeep get quantifiable safety and economic advantages (CBD, 2022; Ministry of Environment, Forest and Climate Change, 2021, 2022, 2023, 2024, 2025).

9. Implications for Management and Policy

A coastal defence strategy need to prioritise the delineation of service units above the establishment of planting units. Every vulnerable community, embankment stretch, jetty, freshwater infrastructure, and evacuation pathway must to be connected to the mangrove belt that affects its wave dynamics. Baseline assessments must document forest breadth, canopy elevation, stem density, root morphology, openings, stream intersections, foreshore altitude, shoreline dynamics, and sediment composition. Following significant storms, the same metrics have to be reassessed via water-level and damage evaluations. This generates the necessary data to assess local protective efficacy.

Secondly, restoration need to be grounded on processes. Hydrological reconnection, sediment deposition or retention, facilitated natural regeneration, and management of grazing or trampling might be more effective than continual planting. The selection of species need to be based on salinity, inundation, wave exposure, and substrate. Natural colonisationneed to be prioritised when propagules and elevation are sufficient, however engineering interventions should be used judiciously to mitigate wave stress or establish stable intertidal zones. One-year survival serves as an implementation metric; however, five-year breadth, structural intricacy, natural recruitment, and elevation increase are more robust outcome metrics.

Thirdly, embankment policy must include residual risk and scheduled maintenance. Critical areas need risk-oriented evaluations prior to cyclone seasons, autonomous quality verification, and public disclosure of violations and rectifications. Assessment of set-back alignment or regulated realignment is warranted when the existing line is consistently compromised and where social protections make land modification viable. Emergency shelters, dependable warning systems, accessible vessels, and safeguarded potable water infrastructures are crucial, since even a preserved mangrove barrier cannot entirely avert surge floods.

Ultimately, the accountability of institutions need to be distributed via a coastal resilience observatory that encompasses forestry, irrigation, disaster management, municipal authorities, academic institutions, and community organisations. A standard geographic database must preserve unprocessed measurements and information, differentiate between reserve-zone and settlement-zone flora, and provide yearly indications. The observatory need to establish assessment frameworks prior to repair, including comparative extents and sensor positioning. This design discipline would transform future cyclones from unrecorded disasters into ethically collected data for enhancing safety measures.

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