

The roles of mangroves in sedimentation: A case study in Sundarbans, India

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Abstract

The Sundarbans, the southern part of the Ganges-Brahmaputra-Meghna Delta, exemplify the complex interaction between mangroves and sedimentation, with a notable annual loss of about 2 sq. km of mangroves and land, especially during post-monsoon and bore tides. Nevertheless, alterations in the sediment dispersal system within the Hooghly River, coupled with various anthropogenic activities, are substantially modifying the dynamic system response of the Indian Sundarbans and, consequently, the role of the mangrove ecosystem in sedimentation, which contradicts the existing literature. Remote sensing analysis from 1922 to 2022 showed that a tidal bar on the Hooghly River's bed lost 1.50 sq. km since 1972 but gained 0.79 sq. km of mangroves. The mangrove proportion increased from 5.29% in 1972 to 51.05% in 2022. The study suggests mangroves might indirectly cause erosion, highlighting the need for sustainable monitoring and urgent conservation efforts to protect this vital ecosystem.

Highlights

- The uninhabited tidal bar lost an area of 0.29 sq. km from 1922 to 2022.
- Mangroves could not grow uniformly across the tidal bar.
- Bank erosion is responsible for land and mangrove loss.

Graphical abstract:

Introduction

Mangrove ecosystems are among the world's most endangered, especially in densely populated regions, such as India and Bangladesh. The Sundarbans, part of the southern Ganges-Brahmaputra-Meghna (GBM) Delta, is one of the largest deltas, supporting endangered plant and animal species threatened by Relative Sea Level Rise (RSLR) (Nandy et al., 2011). RSLR indicates the change in sea surface height relative to land. As a tide-dominated delta with tidal bars stabilised by vegetation, the effects of RSLR are significant there. Vegetation growth and tidal bar formation are interconnected, driven by geological, climatic, soil, and topographical factors. Salt-tolerant swamp trees and halophytic plants thrive in saline conditions, exemplifying the complex interactions within this ecosystem. Studying the Sundarbans enhances understanding of the Ganges-Brahmaputra-Meghna Delta system.

Mangroves are vital coastal ecosystems in tropical and subtropical intertidal zones, providing essential habitats and shoreline protection often undervalued. Species like *Avicennia officinalis* are crucial for local communities. Their unique adaptations, such as aerial roots and tolerance to low-oxygen soils, make them compelling subjects for study — especially for understanding sedimentation and ecological contributions. Additionally, given their economic value that surpasses rehabilitation costs, this research aims to inform conservation and restoration efforts globally.

There is an ongoing debate about how mangroves aid sedimentation. The concept of mangroves as 'land builders' has been central to research, as vertical accretion and soil formation help mitigate sea-level rise and provide essential ecosystem services, including carbon storage, nursery habitats, and shoreline protection. In a detailed study, John H. Davis (1940) demonstrated the sediment buildup and land progradation by mangroves in Florida, resulting in the formation of peat layers beneath the tidal range. Conversely, some geologists see mangroves as opportunistic plants in intertidal marshes with high sedimentation rates (Egler, 1952; Thom, 1967; Scholl, 1968; Bird, 1971). Evidence suggests that mangroves aid sedimentation through peat formation or by accelerating inorganic sedimentation, with biological activities playing a key role (Cahoon et al., 2003; Krauss et al., 2003; McKee et al., 2007; McKee, 2011). However, research on the spatial and temporal impacts of mangroves on sedimentation remains limited (Lee et al., 2014).

The Sundarbans, a vital ecosystem, faces severe impacts from climate events like Cyclones Amphan and Yaas, which damage agricultural lands through saline intrusion, inundation, and erosion (Haque et al., 2024; Pal & Bandyopadhyay, 2024). Bangladesh's Sundarbans encounter additional challenges after cyclones (Sonet et al., 2024). Research on mangroves' role in sedimentation is crucial for supporting the Integrated Coastal Zone Management (ICZM) process (Iftekhara & Islam, 2004), emphasising their significance in environmental and coastal management. These findings on the role of mangroves in erosion will enhance knowledge and guide future conservation and erosion assessment efforts, emphasising the importance of further action in environmental and coastal management.

Kabasgadi Island, on the left bank of the Muriganga River (see Fig. 1), extends from 21°50'11.78"N to 21°52'11.49"N and 88°10'05.49"E to 88°11'39.97"E. Named by the Survey of India in the 1960s, it was surveyed between 1967- 68, covering approximately 1.90 sq. km. It measures 4.41 km in length and 0.12-0.56 km in width, with an average height of ~2 metres above sea level. It forms where Kalnagini Khal, a river from the Saptamukhi River, emerges from the Muriganga (refer to Fig.1). The Muriganga, a distributary of the Hooghly River, branches off near Sagar Island about 2 km north of the island, with the Kakdwip River to the east and the Muriganga to the west (refer to Fig.1). Furthermore, there is no written record regarding the role of vegetation in this tidal bar, despite its erosion-proneness (Chakraborty & Sahoo, 2015).

Materials and Methods

The lack of reliable secondary data on the Sundarbans led to the use of alternative sources. Remote sensing, due to its ability to evaluate and monitor land and mangrove cover changes over time, was a powerful tool given the area's dynamic nature and data scarcity. The research methodology, which combines remote sensing, field surveys, and data validation, ensures the reliability of the findings. The researcher analysed mangrove deforestation, degradation, and sedimentation of a side-channel tidal bar using multi-temporal Landsat data from 1972 to 2022, alongside topographical maps and satellite images (details in Chart 2.1, Table 1). Field surveys were also conducted to explore the interrelationship between erosion and mangroves.

Satellite images and pre-processing of images:

Landsat surface reflectance data, a credible source, were downloaded from the USGS website (<http://earthexplorer.usgs.gov>) from 1988 to 2019 (see Table 1). This data removes noise from atmospheric and illumination effects, ensuring analysis accuracy. LANDSAT 5 (1988- 2011) used a Thematic Mapper (TM) sensor, and LANDSAT 8 (2013- 2021) used an Operational Land Imager (OLI) with 30 m resolution (Chander et al., 2009; Lulla et al., 2013). Images were selected for the post-monsoon and pre-monsoon periods, from November to March, when tide and soil salinity remain stable due to low evapotranspiration (based on the Survey of India Tide Table and field surveys) (see Table 1). This period aligns with the blooming season of *Avicennia officinalis* L. (April- July), commonly used for mangrove change studies (Ghosh et al., 2015; Giri et al., 2007; Pramanik, 2014).

Images were rectified with ground control points (GCPs) collected during field surveys, using ENVI 5.3 for georeferencing, achieving RMSE of 0.10- 0.19 or 3- 5.7 metres. No additional co-registration was required, as all Level 1T Landsat images exhibited high coherence with shifts of less than 1 pixel, which had a minimal impact on the study area.

Mangrove cover: Several remote sensing studies in the Sundarbans mapped mangroves and their changes (Blasco et al., 2001; Dwivedi et al., 1999; Giri et al., 2007; Islam et al., 1997; Paul et al., 2017), focusing on Bangladesh or Indian parts at different times, but most lacked detailed field analysis of the mangroves' role in sedimentation.

The study area was clipped from rectified images (see Table 1), digitised to outline mangrove zones, and the cover over the years was compared (see Tables 1, 2, 3, and Figs. 2, 3, 4).

Accretion/erosion of the tidal bar: The evolution of the tidal bar based on topographical sheets and satellite maps (from 1972 to 2022) was analysed (see Table 1). The area of the tidal bar, using 1922-23 and 1967 topographical sheets, was calculated after georeferencing them (see Tables 1 and 2 and Fig. 2). The boundary of the tidal bar was delineated by digitising the stacked georeferenced LANDSAT images from 1972, 1975, and 1978 (see Table 1).

Rectified satellite images from 1988 to 2022 were then used to further analyse the change in the area of the tidal bar (see Tables 1, 2, and 3, and Figs. 3 and 4). The Modified Normalised Difference Water Index (MNDWI) was calculated for each Landsat image to delineate the extent of the tidal bar. MNDWI was computed using the formula:

$$\text{MNDWI} = (\text{Green} - \text{MIR}) / (\text{Green} + \text{MIR}), (\text{Xu}, 2006)$$

Where MIR is the reflectance of the mid-infrared band and Green is the reflectance of the green band.

Water features produced positive values as they absorb MIR light, while soil and vegetation yielded negative values as they reflect MIR light (Jensen, 2005). Consequently, MNDWI was most effective in defining the boundary of the tidal bar. The area of the tidal bar for each year was then measured (see

Tables 1, 2, and 3, and Figs. 3 and 4). Zone-wise changes in the area were assessed using a graphical method that involved overlaying maps of a base year and subsequent years, and measuring the changes in area using a grid system. This visual method illustrates the fluctuation of the tidal bar's area over time (see Tables 1, 2, and 3, and Figs. 3 and 4).

Field survey: Remote-sensing data analysis does not replace field surveys, although getting into swamps of mangrove forests is challenging, and conducting field inventory takes time and effort (Giri et al., 2007). Field surveys, a crucial and irreplaceable component of this research, were conducted to validate the remote sensing-based analysis. From 2016 to 2021, the zone-wise vegetation density (number of trees per sq. km) and average vegetation height were measured manually by Abney level and tape, respectively (see Table 4 and Fig. 5). This meticulous on-ground verification, which involved measuring the chronological changes in tree erosion imprints using measuring tape and GPS (see Table 5 and Plates 1 and 2) adds a layer of reliability to the remote sensing data, enhancing the robustness of the study to analyse the crucial roles of the mangroves in erosion.

Furthermore, the research identified a significant correlation between net land gain and changes in mangrove coverage. Employing orthogonal regression analysis (refer to Table 3 and Fig. 4), which accounts for errors in both variables, this relationship enhances our understanding of tidal bar dynamics. It contributes to the development of effective conservation and management strategies for mangroves.

Result

1922-1988: Kabasgadi Island, a unique landform, was formed through the process of sedimentation. In 1922-23, the Kakdwip Sand bar, covering 2.19 sq. km, submerged during high tide (see Table 2 and Fig. 2). Over time, the two sandbars, Kakdwip and Minx, merged, creating a larger island of 3.27 sq. km in 1967-68 (see Table 2 and Fig. 2), expanding by about 1.08 sq. km over 45 years.

Landsat images from 1972 show a 0.13 sq. km increase in five years (see Table 2 and Fig. 2). Finally. By 1975, the two bars merged south of the island, with the island losing 0.10 sq. km between 1972 and 1975, then gaining 0.03 sq. km from 1975 to 1978 (see Table 2 and Fig. 2).

Vegetation diversifies over time; mangroves increased by 0.24 sq. km (7.43%) from 1972 to 1975 and multiplied sixteenfold from 1975 to 1978 (see Table 2 and Fig. 2). Despite growth from 1975 to 1988, the island lost 0.59 sq. km of land and 0.05 sq. km of mangroves, with mangroves increasing by 4% to the total area, indicating the role of erosion in the loss from 1978 to 1988 (see Table 2 and Fig. 2). The land accretion stalled after 1988, marking a decline due to land loss (see Table 2 and Fig. 2).

1988-2022:

Over the years, Kabasgadi Island has undergone fluctuations and significant transformations in its area, primarily due to tidal patterns, sedimentation, and the growth of vegetation. This has divided the tidal bar into three zones, each with distinct vegetation and erosion patterns. Our research helps understand and

preserve these coastal ecosystems. Areas above 21°51'30"N and below 21°50'30"N are zones I and III, respectively (see Fig. 3). The area between 21°50'30"N and 21°51'30"N is zone II (see Fig. 3).

First zone: From 1988-94, land loss (~0.008 sq. km) was offset by mangrove growth (~0.15 sq. km) in zone one (see Table 3 and Figs. 3 and 4). Afterwards, both areas declined until 2009. From 2009- 11, land accreted (~0.009 sq. km), with mangroves stable (see Table 3 and Figs. 3 and 4). Land growth and mangrove expansion resumed until 2015, despite a 0.04 sq. km mangrove loss from 2015-18 (see Table 3 and Figs. 3 and 4). In 2018-19, land area shrank (~0.008 sq. km) while mangroves grew (~0.02 sq. km) (see Table 3 and Figs. 3 and 4). Between 2019-21, both land (~0.012 sq. km) and mangroves (~0.06 sq. km) increased (see Table 3 and Figs. 3 and 4). In 2021-22, land declined (~0.018 sq. km) with mangroves expanding (~0.03 sq. km) (see Table 3 and Figs. 3 and 4). Overall, land decreased (~0.028 sq. km) from 1988- 2022 despite mangrove growth over 0.14 sq. km (see Table 3 and Figs. 3 and 4).

Mangroves showed resilience: absent in 1988, they colonised the entire zone by 1994, vanished by 2009, and reestablished by 2013, reaching near full Coverage by 2022 (see Fig. 3), with the proportion of mangroves to the total land increasing from 45.21% to 51.05% (refer to Table 2 and Figs. 3 and 4). A positive correlation ($r = 0.179$) and slope ($b = 0.05$) between mangrove (x) and land (y) growth indicate the resilience of sediment accretion (refer to Table 3 and Fig. 4).

The **second zone** exhibits a different trend from the first, with mangrove growth occurring despite land loss of approximately 0.009 sq. km. during 1988-1994, accompanied by gains of about 0.61 sq. km. during this Period (see Table 3 and Fig. 3 and 4). Similar trends were observed in the periods 1997-2000, 2009-2011, 2019-2021, and 2021-2022, where mangroves expanded by approximately 0.66, 0.18, 0.09, and 0.11 sq. km., respectively, despite land losses of 0.009, 0.018, 0.037, and 0.057 sq. km. (see Table 3 and Fig. 3 and 4). This trend was disrupted when land and mangrove changes aligned, such as during 2011-13, when both increased, and 1994-97, 2000-06, 2006-09, 2013-14, 2014-15, and 2015-18, when both declined (see Table 3 and Fig. 3 and 4). Despite a land loss of 0.035 sq. km. In 2018-19, mangroves showed no change; however, overall, from 1988 to 2022, both land (0.302 sq. km.) and mangroves (0.04 sq. km.) declined (see Table 3 and Fig. 3 and 4). The area was full of mangroves in 1994, with colonisation beginning in 1988, and experiencing fluctuations due to events like Cyclone Aila (see Fig. 3). Despite ongoing losses, the resilience of mangroves is promising, with potential for vertical peat accumulation, which aids their adaptation. Moreover, the positive correlation coefficient (0.313) and the slope (0.015) of the relationship between mangrove growth (x) and land gain (y) in this zone indicate the potential resilience of sediment accretion to mangrove growth, analogous to the first zone (see Table 3 and Fig. 4).

The **third zone** lost approximately 0.041 sq. km, despite mangroves growing over 0.59 sq. km from 1988 to 1994 (see Table 3 and Figs. 3 and 4). Mangroves increased by 0.57 sq. km, despite a 0.075 sq. km loss between 1994 and 1997, then declined until 2014 (see Table 3 and Figs. 3 and 4). Between 1999 and 2000, peat and sediment accretion resulted in a land gain of 0.012 sq. km (see Tables 2 and 3 and Figs. 3 and 4). In 2014-15, mangroves expanded by ~0.04 square kilometres, despite experiencing land

loss since 2000, possibly due to densification and increased resilience (see Table 3 and Figs. 3 and 4). Between 2014 and 2021, no net mangrove growth occurred; however, overall, mangroves grew by ~0.02 square kilometres, while a loss of 0.513 square kilometres was recorded from 1988 to 2022 (see Table 3 and Figs. 3 and 4).

Initially, mangroves lost area by 1988 but expanded across the zone by 2000; however, they were subsequently deforested by road and ferry construction, inhibiting regrowth (see Figs. 3 and 4). Negative correlations of -0.189 and -0.141 indicate that erosion has an adverse impact on sediment and mangrove growth (see Table 3 and Fig. 4).

The distribution of mangroves changed across all zones, demonstrating resilience in the face of cyclones, earthquakes, human activity, increased sedimentation, and sea-level rise (see Tables 2 and 3 and Figs. 3 and 4). These changes highlight the need for urgent surveys to analyse the complex interrelationships of mangroves, erosion, and sedimentation, given their spatial and temporal variability.

The changes on Kabasgadi Island highlight urgent concerns. These include increased vulnerability to sea-level rise and damage to ecosystems. Since 1988, erosion of the tidal bar and modifications from natural events, such as cyclones and earthquakes, have emphasised the need for field surveys to analyse mangrove-erosion relationships, as changes vary across the tidal bar (see Tables 2, 3, Figs. 3, 4).

The first zone, characterised by fluctuating vegetation and minimal height growth, remains affected by hyper-salinity from the 2018 earthquake, exacerbated by cyclones Komen, Roanu, Ockhi, and Mora, which resulted in significant vegetation loss (see Figs. 3 and 4, Tables 2 and 3). Human activities, such as illegal wood harvesting for construction and brickfields, have also disrupted mangroves, leading to deforestation and the formation of hypersaline patches (see Table 2 and Figs. 3 and 4). Despite these issues, the area of the mangroves to the total area increased by approximately 20.03 km² from 1988 to 2022, peaking at 82.09% of the area in 1994 and then declining to 31.02% by 2022, indicating a potential for recovery that was hindered by interventions (see Table 2 and Figs. 3 and 4).

Field surveys conducted across 2018-2019 revealed patterns in mangrove growth, with zones two and three showing increased density (~74.75 and ~79.75 trees per square kilometre) and height (~2.98 m and ~5 m) (see Table 4 and Fig. 5). Zone I remained challenging, with no height increase and ~2.75 trees per sq. km (see Table 4 and Fig. 5). Titli, Gaja, and Phethai, along with earthquakes, causing significant damage. The accelerating rate of anthropogenic activities and other natural factors during 2018-19 further hindered the growth of the mangroves, underscoring the urgent need for action (see Table 2 and Figs. 3 and 4).

However, the field survey on the 21st of March validates the ecological succession over the years by accelerating the rate of vegetation density (50, 100 and 115 trees per sq. Km) and height (~1, ~3 and ~7.10 metres) in all three zones (see Table 4 and Fig. 5), with cyclones Fani, Bulbul, Amphan, Yaas, Gulab, Shaheen, and Jawad impacting the ecosystem, underscoring the need for robust management.

Despite natural disasters, forest restoration efforts, such as tree planting, proved successful, especially in Zone I, demonstrating ecosystem resilience and the importance of human intervention (see Figs. 3 and 4, and Table 2). Monitoring mangrove roles in erosion became crucial, reflecting the scientific rigour of our research.

The forest officials' tree plantation initiative has proven effective against supercyclones like Yaas, Gulab, Shaheen, and Jawad, as shown in Figs. 3-5 and Tables 2-4. Despite natural disasters, the success in the first zone highlights the resilience of mangroves and the potential of human intervention to mitigate the impacts of disasters, a key point for policymakers. However, erosion persisted, making field monitoring of mangroves' role in erosion essential. Research revealed that flood tides involving uprooted trees or debris worsen riverbank erosion (see Table 5, Plate 1). The circular movement of tree branches flowing along with the flood tide creates holes at the riverbank through hydraulicking and quarrying, thereby accelerating erosion (see Table 5, Plate 1(5)). Hydraulic action and soil piping during tides form cracks and holes, with crabs contributing to soil loss and slumping (see Table 5, Plate 2). Field surveys conducted from 2016 to 2021 confirmed that land erosion caused mangrove loss, primarily driven by hydraulic action, climate hazards, and human activities, with soil and hydraulic processes being the dominant factors (refer to Chart 2).

Discussion

The Ganges–Brahmaputra-Meghna (GBM) delta system, a truly unique and awe-inspiring natural wonder, has evolved through a captivating interplay of tectonic processes, eustatic sea-level rise, and the immense and variable fluvio-marine sediment load of the Ganges and Brahmaputra rivers, their tributaries, and the Bay of Bengal, currently estimated at 1 billion tons/year (Goodbred et al., 2003). This exceptional ecosystem, a testament to our planet's abundant biodiversity, is home to the mangroves, a unique and vital part of our natural world. The mangroves, with their diverse array of plant and animal species, are a living testament to the richness and importance of our natural world. However, its staggering degradation rate is a cause for serious concern. Over the past 237 years (1776-2013), an average of 0.2% of mangroves have been lost yearly, totalling 46.89% (Ghosh et al., 2015; Sarangi & Misra, 2016). The degradation of this unique gem on our planet's landscape is not a distant threat but a present peril that demands immediate and concerted intervention.

In this delta, the tidal rivers receive sediments from the upper and middle basins through natural freshwater flow and from the ocean via the tide, gradually forming the tidal bars where the flood and ebb tide currents converge. Gradual sedimentation on this newly formed tidal bar increases its mean elevation above the water surface. As the sediment-laden water becomes firm enough to support emergent vegetation, the mangrove seeds gradually start germinating when the bar no longer submerges during low tide, except during monsoon, spring, and bore tides (Bloom, 2003). The mangrove seeds flow inside the tidal bar during high tide and germinate there because these seeds are no longer carried away by the relatively elevated land. As the flood flow enters the tidal bar perpendicular to the shoreline, the mangroves grow in a linear or elongated pattern on the tidal bar, as observed from 1972 to

1978 (see Fig. 2). The Hatkonch Kanta (*Acanthus iticifolius*), Hental (*Phoenix paludosa*), and Baen (*Avicennia officinalis*) grow as vegetation in this second stage, succeeding the saline grasses (Banerjee, 1964; Naskar et al., 1987). Between 1972 and 1978, the tidal bar accumulated and lost sediments, resulting in the formation of a tidal bar in the south (see Table 2 and Fig. 2). However, it has undergone erosion since 1988 (see Table 2 and Figs. 2, 3 and 4). Moreover, the study area experienced early ecosystem growth before 1972 (refer to Fig. 2); thereafter, mangroves began to dominate the ecosystem.

The colonisation of the mangroves begins in the south, or zone III, because the flood tide carries mangrove seeds and reaches the southern part of the bar first during semi-diurnal tides (see Figs. 2 and 3). As the south of the tidal bar got elevated by gradual sedimentation and received early colonisation of the mangroves, the mangroves became healthier and denser in the south than in the rest of the area (see Figs. 2 and 3).

Gradually, the mangrove colonised species-wise over the years and formed dense forests. *Avicennia officinalis* predominantly colonises Kabasgadi Island. This species of mangrove is the fastest-growing among its counterparts (Kitaya et al., 2002). If favourable conditions prevail, it takes barely two to three years to grow up to 1 metre. Although *Avicennia officinalis* is a salt-resistant species, it generally prefers to grow on moderately saline soil (Patel et al., 2013). Mangroves have thrived in these challenging conditions with their unique adaptations and resilience. They neutralise the salts in the soil, and their pneumatophore and root network help them grow fast and healthy.

Kabasgadi Island is home to Baen (*Avicennia officinalis*), one of the fastest-growing mangrove species (Kitaya et al., 2002). Consequently, this tidal bar was expected to support a dense mangrove forest. However, it remains insufficiently covered by lush mangroves. Since 1988, the mangrove ecosystem on this newly formed compound tidal bar has encountered numerous challenges, preventing it from reaching climax succession across the entire area. Currently, the vegetation on Kabasgadi Island is still in the second stage of succession, as mangrove plants have not yet fully colonised the area, with the average height of the mangroves being approximately 4 metres (see Table 4 and Fig. 5). The potential loss of this unique ecosystem constitutes a matter of significant concern and urgency.

The hydrodynamic regime and human activities, such as earth mining, have had a profound and detrimental impact on the flora and, consequently, the tidal bar since 1988 (see Table 2 and Figs. 3 and 4). This year marked a turning point when the tidal bar began to lose its area. The intensity of human interference has escalated in recent years due to its proximity to the urban sprawl of Kakdwip (see Table 2). Each year, one or two factors predominantly accelerate the decline of mangroves in different zones at various rates; however, the role of other factors in mangrove degradation cannot be ignored (see Table 2).

Furthermore, given its proximity to the Bay of Bengal at a distance of 30 km and its location along the Muriganga River, the study area is susceptible to tropical cyclones. These cyclones, including the 'Kalbaisakhi,' a local storm and flood occurring nearly annually in the upper valley, generate destructive

winds and intense rainfall-induced floods. The wind velocity from the western side during such storms, particularly over the Muriganga River, exceeds that of the eastern side, which is closer to Kakdwip, as cyclones tend to advance inland along the Hooghly River. This cyclone-induced gusty wind flow results in the uprooting of more trees on the western bank than on the eastern bank of the tidal bar, thereby accentuating the area's susceptibility to erosion, as has been observed. It is imperative to comprehend these dynamics and their influence on mangrove growth, especially in the context of climate change and the increasing frequency of such cyclonic events.

Moreover, the cyclones and torrential rain bring other hindrances to mangrove growth and tidal bar progradation. When the tidal bar submerges during monsoons, spring tides, bore tides, and cyclones, the water fills the lowland and remains there until it evaporates. After evaporation, this water leaves salt on the soil surface, which penetrates deep inside the soil due to leaching during the next rainfall, making the entire soil profile saline. This high salinity in the soil hampers the growth of mangroves, which are not adapted to such conditions, leading to a decline in their population and a loss of their ecological services (Paul et al., 2017). Moreover, when the temperature again rises after rain, the upward movement of saline water leaves salt on the soil surface. Gradually, salt flats form through these repetitive processes. During the monsoons, the influx of freshwater helps decrease the salinity of the river water; however, suspended sediments and water are deposited on the low-lying flats of the tidal bar and in the water during submergence. When the water evaporates, the salt and suspended sediments are left on the soil surface, contributing to the formation and expansion of the salt pan (Paul et al., 2017). In this way, the tidal bar has experienced significant yearly setbacks after cyclones, particularly after Aila in 2009 and Amphan in 2021 (see Tables 2 and 3, Figs. 3 and 4).

The highest mangrove growth during 1988-94 represented the natural succession of the mangrove despite land loss (see Table 2 and Figs. 3 and 4). The neutralisation of the salt by the mangroves in the northern part (zone I) is often precluded due to continuous submergence during monsoons, spring tides, bore tides, and cyclones, resulting in the formation of salt flats (refer to Plate 3). Moreover, a lower elevation (~1 metre) from the Mean Sea Level (MSL) of zone I than the rest of the parts of the tidal bar allows the long duration of submergence in saline water, as observed during the field surveys. Dwarf mangroves (the mangroves have a height $\leq$ 1 metre) are observed in the first zone as the expression of salt flat formation (see Plate 3); despite the efforts of the Forest Department officials to afforest Zone I, earth mining and excess salinity precluded the mangrove growth (see Plate 3). The cyclone's impact is vivid in the first zone, especially after the supercyclone 'Aila' in 2009, when, despite the sediment accretion, mangroves were lost; however, the salt-neutralising capability and homeostasis of the mangrove ecosystem led to both mangrove growth and land accretion (see Tables 2 and 3 and Figs. 3 and 4). However, the supercyclone Mora again hindered the mangrove growth despite sediment deposition (see Tables 2 and 3 and Figs. 3 and 4). The intervention by the Forest department, which includes the plantation of the Baen (*Avicennia officinalis*), did not allow the repetition of this loss of mangroves despite sedimentation post-Amphan in 2021, showed positive growth, which continued till 2022 despite land loss (see Tables 2 and 3 and Figs. 3 and 4). Therefore, cyclones, earthquakes, hydrodynamic erosion, salinity, and anthropogenic factors act as perturbations in mangrove growth in

the first zone, with a positive feedback system, as these events expedite land loss and salinisation (see Tables 2 and 3 and Figs. 3 and 4). Hence, the mangroves have played insignificant roles in sedimentation in the first zone; instead, the erosion results in mangrove loss since 1988 (0.022 sq. Km compared to 2019 and 0.028 sq. Km compared to 2022) (see Tables 2 and 3 and Figs. 3 and 4) mangrove loss since 1988 (0.022 sq. Km compared to 2019 and 0.028 sq. Km compared to 2022) (see Tables 2 and 3 and Figs. 3 and 4).

The second zone also demonstrates a similar pattern of the highest mangrove growth during 1988-94, signifying the natural progression of the mangrove despite land loss (see Tables 2 and 3, and Figs. 3 and 4). However, this zone commenced to experience a decline in mangrove cover until 2009, when sediment accretion facilitated vegetation growth (0.18 sq. km), notwithstanding land loss (0.018 sq. km). This indicates vertical sediment accretion during 2009-11, leading to an increase in both land (0.009 sq. km) and mangrove area (0.03 sq. km) during 2011-13 (refer to Tables 2 and 3, and Figs. 3 and 4). The construction of brickfields on the opposite bank, along with the remodelling of Kakdwip harbour, attracted earth miners to this zone, resulting in the loss of both land and mangroves from 2013 to 2018, and consequently, no mangrove growth during 2018-19 (see Tables 2 and 3, and Figs. 3 and 4). Nonetheless, the Forest Department's plantation of Baen (*Avicennia officinalis*) successfully revitalised mangrove growth, underscoring the vital role of human intervention in mangrove restoration. Regrettably, the mangroves could not withstand land erosion, which has been intensifying due to the limited sedimentation role of mangroves, as substantiated by field measurements (refer to Table 5 and Plates 1, 2, 4 and 5).

In zone 2, the formation of hypersaline banks is a pivotal geographical characteristic. These banks may have formed as a consequence of the banks submerging twice daily during semi-diurnal high tides. Furthermore, the development of hypersaline banks could be more extensive on the eastern side, which possesses a gentler slope than the western bank, particularly in zone II, as documented during field surveys. This research insight offers a valuable understanding of the area's distinctive geographical features. Accordingly, the hypersaline tracts and banks are predominantly populated by saline grasses, with occasional presence of dwarf mangroves. The prolonged submergence of the tidal bar during the monsoon season led to sedimentation. Consequently, excessive sedimentation on the pneumatophores leads to their clogging, which in turn causes mangrove mortality. Nevertheless, the level of salinisation in this zone is lower compared to the first zone, as this area is situated at a higher elevation, attributed to increased sediment accretion and vertical peat development by the initially colonising mangroves (see Figs. 2 and 3; Tables 2 and 3). These findings substantially enhance the understanding of the complex interactions between sedimentation processes and mangrove growth.

In Zone 2, in addition to salinity, human activities such as earth mining, road construction, fishing (refer to Plate 4), and trawler movement contribute to the erosion of the east bank, as observed during the field surveys (see Table 2). Plate 4 vividly illustrates the detrimental impact of fishing in the tidal creek, where ropes tied to the trees (see Plate 4 (1)) lead to their collapse. However, the Forest Office has taken measures to curb fishing along the tidal courses, as observed during the field survey (see Plate 4 (2)).

Hence, cyclones, earthquakes, salinity, and human activities can be viewed as disturbances to mangrove growth (see Tables 2, 3, 4 and 5, Figs. 3, 4 and 5). Despite showing the highest mangrove growth due to natural growth during 1988-94, the second zone lost mangroves compared to 1988 (about 0.24 sq. Km in 2019 and 0.04 sq. Km in 2022) (see Table 3 and Figs. 3 and 4). This underscores that land loss due to bank erosion is the primary factor influencing mangrove growth, rather than the mangroves impacting sedimentation. Nevertheless, the positive correlation coefficient (0.31) indicates a promising prospect for sediment resilience as a potential solution to mangrove growth (see Table 3 and Fig. 4).

The third zone, in line with the trend of natural succession demonstrated by the rest of the zones during 1988-1994 (see Table 3 and Figs. 3 and 4), exhibited mangrove growth that continued until 1997, despite land loss (see Table 3 and Figs. 3 and 4). The vertical accretion allowed mangrove growth for the first and last time, approximately 0.012 sq. Km during 1997-2000 (see Table 3 and Figs. 3 and 4). After that, the mangrove lost in tune with the land loss from 1997 to 2014 (see Table 3 and Figs. 3 and 4). Positive mangrove growth was again observed during 2014-15, due to the absence of supercyclones (see Table 3 and Figs. 3 and 4). However, after that, this zone has been experiencing both land and mangrove loss, despite gaining about 0.03 sq. Km and 0.02 sq. Km areas of mangroves in 2019 and 2022 as compared to 1988 (see Table 3 and Figs. 3 and 4).

The colonisation of mangroves in Zone III initiated soil salinity neutralisation, a testament to their resilience and adaptability. However, this zone still has a few patches with no mangrove trees along the east bank, as observed during the field surveys (see Fig. 3). The majority of Zone III is covered by dense, tall mangroves with a few patches of grasslands (see Table 3 and Figs. 3 and 4). Despite the presence of these mangroves, Plate 2.5 illustrates that riverbank erosion remains a significant challenge. This erosion, induced by natural factors such as cyclones and earthquakes, hydraulic erosion, salinity, and, significantly, human activities, including trawler movement and embankment construction at the opposite bank, has contributed to the perturbations in the system of mangrove growth (see Tables 2, 3 and 5 and Figs. 3, 4 and 5).

Therefore, it is reasonable to infer that mangroves may only establish growth in areas where the tidal bar experiences vertical accretion via peat formation. However, they are unable to withstand bank erosion. The intricate interplay of numerous factors, predominantly the hydrodynamic properties of the slough channel and the Muriganga River, has historically influenced the composition of flora, as well as erosion processes and the development of the tidal bar from 1922 to the present day.

Conclusion

It can be concluded that the Kabasgadi Island accreted sediment till 1988. After that, the complex of simultaneously acting perturbations, each with its unique impact, altered the tidal bar's morphology zone-wise through a negative feedback system for achieving long-term equilibrium (see Fig. 4). Thus, the growth of the tidal bar ensued from the gradual sedimentation at the place where the ebb and flood tides meet, the subsequent colonisation of mangroves, in contrast, bank erosion has resulted in the shoreline

retreat and mangrove loss as experienced by the tidal bar since 1988 (see Tables 2 and 3 and Figs. 2, 3 and 4).

Geology, topography, and climate influence the tidal bank and mangroves, leading to a decrease in the island's area and a reduction in the proportion of mangroves. Despite the growth of mangroves, land loss due to erosion remains considerable, challenging the notion that mangroves promote accretion, as they typically flourish on higher ground. The inverse relationship between sediment accretion, mangrove expansion, and bank erosion suggests a weak correlation. Therefore, mangrove growth primarily depends on sedimentation in tide-dominated deltas, making sedimentation vital for their resilience.

Despite extensive remote sensing studies, literature, in-situ measurements, and observations, more research is needed to understand the complex relationship between mangrove growth, land erosion, and other factors at the micro-scale. This highlights ongoing scientific inquiry and our role in advancing understanding of these vital ecosystems.

This research highlights risks to Kabasgadi Island's ecosystem and vulnerability to sea-level rise. Changes in island area and vegetation indicate an impending crisis, highlighting the island's susceptibility to coastal hazards and the resilience of its ecosystem. It notes mangroves' negative impact on sedimentation, offering climate change insights in tide-dominated deltas (Nguyen-Xuan et al., 2024; Rajakumari et al., 2024). Immediate action is crucial, as the research can have a significant impact on policy.

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Author contributions: CRediT

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Tables

Table 1: Details of the dataset used in this study

Satellite Images				
Sensor	Date	Band	Wavelength (mm)	Source
LANDSAT 1 MSS	5.11.1972	All	0.5-1.1	USGS Earth Explorer (http://earthexplorer.usgs.gov)
LANDSAT 2 MSS	5.12.1975 25.12.1978	All	0.5-1.1	
LANDSAT 5 TM	26.12.1988 25.01.1994 01.11.1997 27.12.2000 12.12.2006 04.12.2009 08.11.2011	Band 2 (Green) Band 5 (SWIR 1)	0.52-0.60 1.55-1.75	
LANDSAT 8 OLI	15.12.2013 08.12.2014 19.11.2015 11.01.2018 30.01.2019 08.03.2021 03.03.2022	Band 3 (Green) Band 6 (SWIR 1)	0.53-0.59 1.57-1.65	
Topographical Sheets				
Sheet number	Survey year	Year of publication	Source	
79 C/1	1922-23	1942	Survey of India office, New Delhi and National Atlas and Thematic Mapping Organisation (NATMO) office, Kolkata	
	1967-68	1971		

Table 2: Estimate of chronological change of the land and mangrove areas of the tidal bar (sq. km) from 1922 to 2022

Year	Total land area (sq. Km.)	Change in the land area (sq. Km.)	Total mangrove area (sq. Km.)	Change in the mangrove area (sq. Km.)	% of mangroves to the total area	Reasons
1922-23	2.19					Cyclone Bhola in 1970, cyclone Bay of Bengal 03 in 1981, earthquakes in 1918, 1923, 1930, 1934, 1935, 1943, 1950 and 1954, and the Assam flood in 1950
1967-68	3.27	1.08				
1972	3.40	0.13	0.18		5.29	
1975	3.30	-0.10	0.42	0.24	12.73	
1978	3.33	0.03	0.90	0.48	27.03	
1988	2.74	-0.59	0.85	-0.05	31.02	
1994	2.68	-0.06	2.20	1.35	82.09	Flood in 1987, earthquake in 1988, cyclone Bay of Bengal 03 in 1988, typhoon Gay/ Kavali in 1989 and Bangladesh cyclone 01 in 1991
1997	2.56	-0.12	1.90	-0.30	74.22	Earthquakes in 1997 and the cyclone Bay of Bengal 07 in 1997
2000	2.54	-0.02	2.05	0.15	80.71	Cyclones Bay of Bengal 06 in 1998, Odessa supercyclone and earthquake in 1999
2006	2.39	-0.15	1.41	-0.64	59.00	Flood in September 2000, Aquacultural ponds and road constructions in 2000 and 2006, earthquakes in 2001, 2003, 2004 and 2006, and cyclones Bay of Bengal 04 in 2000 and cyclones Bay of Bengal 03 in 2002
2009	2.28	-0.11	0.83	-0.58	36.40	Cyclones Sidr in 2007, Cyclones Rashmi in 2008 and earthquakes in 2008 and 2009
2011	2.22	-0.06	0.94	0.11	42.34	Cyclones Aila and Phyan in 2009, and earthquakes in 2010 and 2011

2013	2.19	-0.03	0.99	0.05	45.21	Kakdwip Harbour was established in 2011
2014	2.20	0.01	0.90	-0.09	40.91	Brickfield construction and remodelling of Kakdwip Harbour
2015	2.18	-0.02	0.92	0.02	42.20	Earthquakes in 2014
2018	2.14	-0.04	0.70	-0.22	32.71	Supercyclone Komen in 2015, Cyclones Roanu in 2016 and Mora and Ockhi in 2017, human intervention
2019	2.07	-0.07	0.69	-0.01	33.33	Cyclones Titli, Gaja and Phethai in 2018 and Earthquakes in 2018, humans' intervention
2021	1.99	-0.08	0.84	0.15	42.21	Cyclones Fani and Bulbul in 2019 and cyclones Amphan in 2020, human intervention
2022	1.90	-0.09	0.97	0.13	51.05	Cyclones Yaas, Gulab, Shaheen and Jawad in 2021, humans' intervention

[Source: Topographical sheets and LANDSAT image-based analysis, Indian Meteorological Department, Kolkata, and personal communication with the Forest officials and local inhabitants]

Table 3: Estimate of zone-wise net change of the land and mangrove areas of the tidal bar (sq. km) from 1988 to 2022

Year	Zone I		Zone II		Zone III	
	Land area	Mangroves area	Land area	Mangroves area	Land area	Mangroves area
1988-94	-0.008	0.15	-0.009	0.61	-0.041	0.59
1994-97	-0.026	-0.07	-0.025	-0.80	-0.075	0.57
1997-2000	-0.015	-0.01	-0.009	0.66	0.012	-0.50
2000-06	-0.001	-0.03	-0.042	-0.30	-0.114	-0.31
2006-09	-0.010	-0.04	-0.035	-0.39	-0.061	-0.15
2009-11	0.009	0.00	-0.018	0.18	-0.051	-0.07
2011-13	0.001	0.04	0.009	0.03	-0.038	-0.02
2013-14	0.030	0.01	-0.011	-0.04	-0.015	-0.06
2014-15	0.002	0.02	-0.004	-0.04	-0.018	0.04
2015-18	0.004	-0.04	-0.029	-0.15	-0.015	-0.03
2018-19	-0.008	0.02	-0.035	0.00	-0.025	-0.03
2019-21	0.012	0.06	-0.037	0.09	-0.053	0.00
2021-22	-0.018	0.03	-0.057	0.11	-0.018	-0.01
1988-19	-0.022	0.05	-0.208	-0.24	-0.442	0.03
1988-2022	-0.028	0.14	-0.302	-0.04	-0.513	0.02
Orthogonal regression of mangrove area (x) and land area (y)						
Parameters	Orthogonal Estimate					
	Zone I	Zone II	Zone III	The Kabasgadi Island as a whole		
Intercept	-0.003	-0.023	-1.883	2.898		
Slope	0.050	0.015	-47.852	-0.405		
Correlation coefficient	0.179	0.313	-0.189	-0.141		

[Source: LANDSAT image-based analysis]

Table 4: Field observation of mangrove density (number of trees per square kilometre) and approximate average mangrove height (metres) (2016-2021)

Dates	Mangroves density			Approximate average mangrove height		
	Zone I	Zone II	Zone III	Zone I	Zone II	Zone III
23 rd April 2016	10	20	50	1.00	1.10	2.05
23 rd August 2016	9	21	55	1.01	1.32	2.07
29 th December 2016	8	22	50	0.90	1.20	2.01
24 th April 2017	7	34	68	1.00	2.00	2.90
20 th July 2017	10	45	75	1.00	2.10	3.50
24 th December 2017	15	40	60	1.00	1.90	3.00
18 th June 2018	20	65	69	0.89	3.00	5.10
21 st August 2018	30	75	80	1.00	3.01	5.60
21 st December 2018	25	70	70	1.00	2.90	6.15
21 st March 2019	20	89	100	0.90	3.00	6.00
10 th March 2021	50	100	115	1.00	3.00	7.01

[Based on field surveys from 2016 to 2021 by the research scholar]

Table 5: Field Observation of Erosion Utilising Tree Parts as Erosion Tools

Sampling points	Tools	Geomorphic Agents	Geomorphic processes	Changes			Plate number
				Dates	Width	Depth	
1	Tree branch	Flood tide	Wave action, hydraulicking, and quarrying	10 th March 2021	1 metre	0.04 metres	1
2	Tree roots and crabs	Tides	Wave action, hydraulicking and soil piping	23 rd April 2016	Length 0.5 metres	0.01 metres	2
				21 st March 2019	Length 0.5 metres, width 0.67 metres	0.89 metres	
				10 th March 2021	Length 0.65 metres, width 1 metre	1 metre	

[Based on field surveys from 2016 to 2021 by the research scholar]

Plates

Plates are available in the Supplementary Files section.

Charts

Charts are available in the Supplementary Files section.

Figures

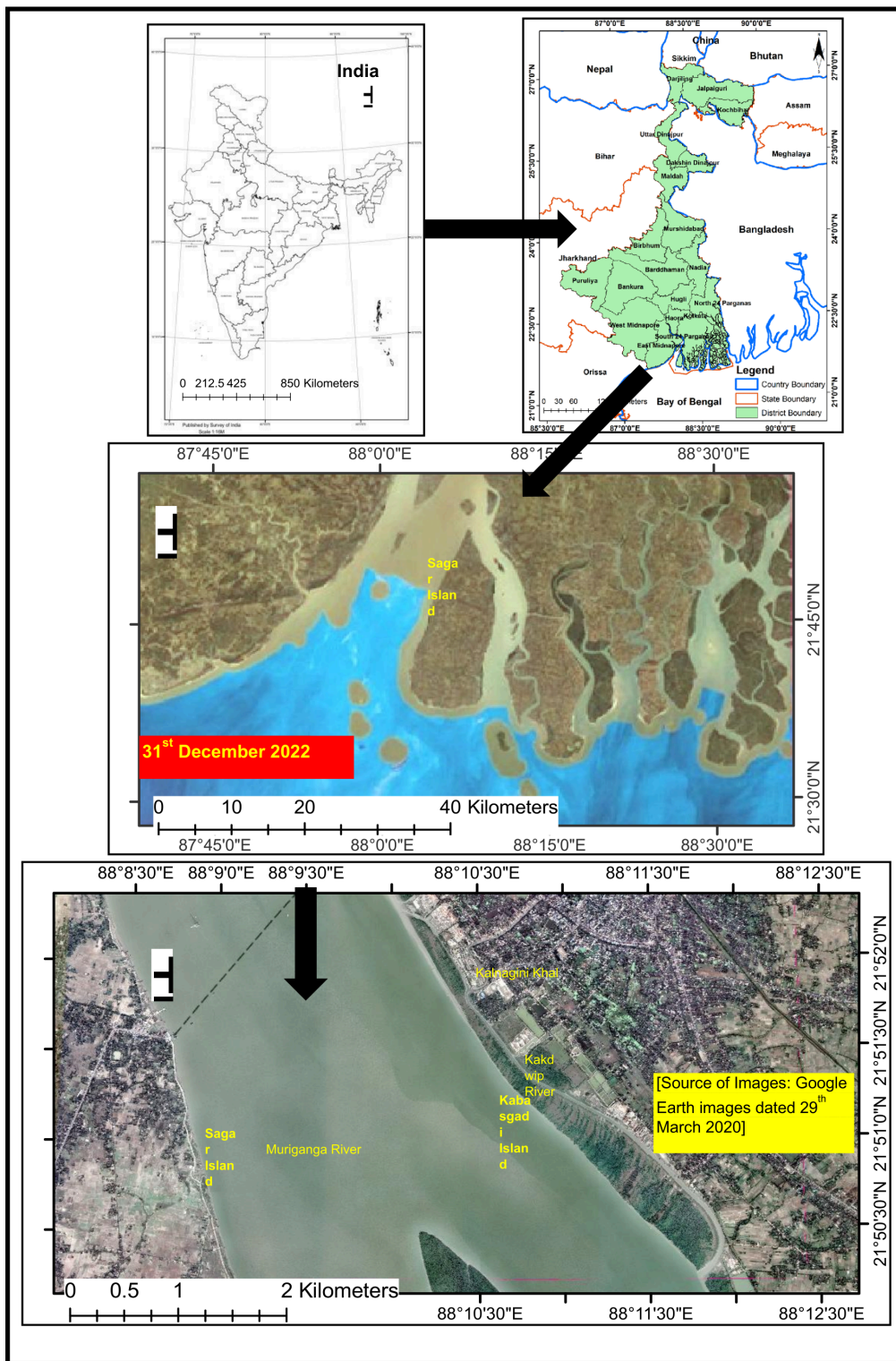


Fig. 1 Location of the study area in the Indian part of the Sundarbans

Figure 1

See image above for figure legend

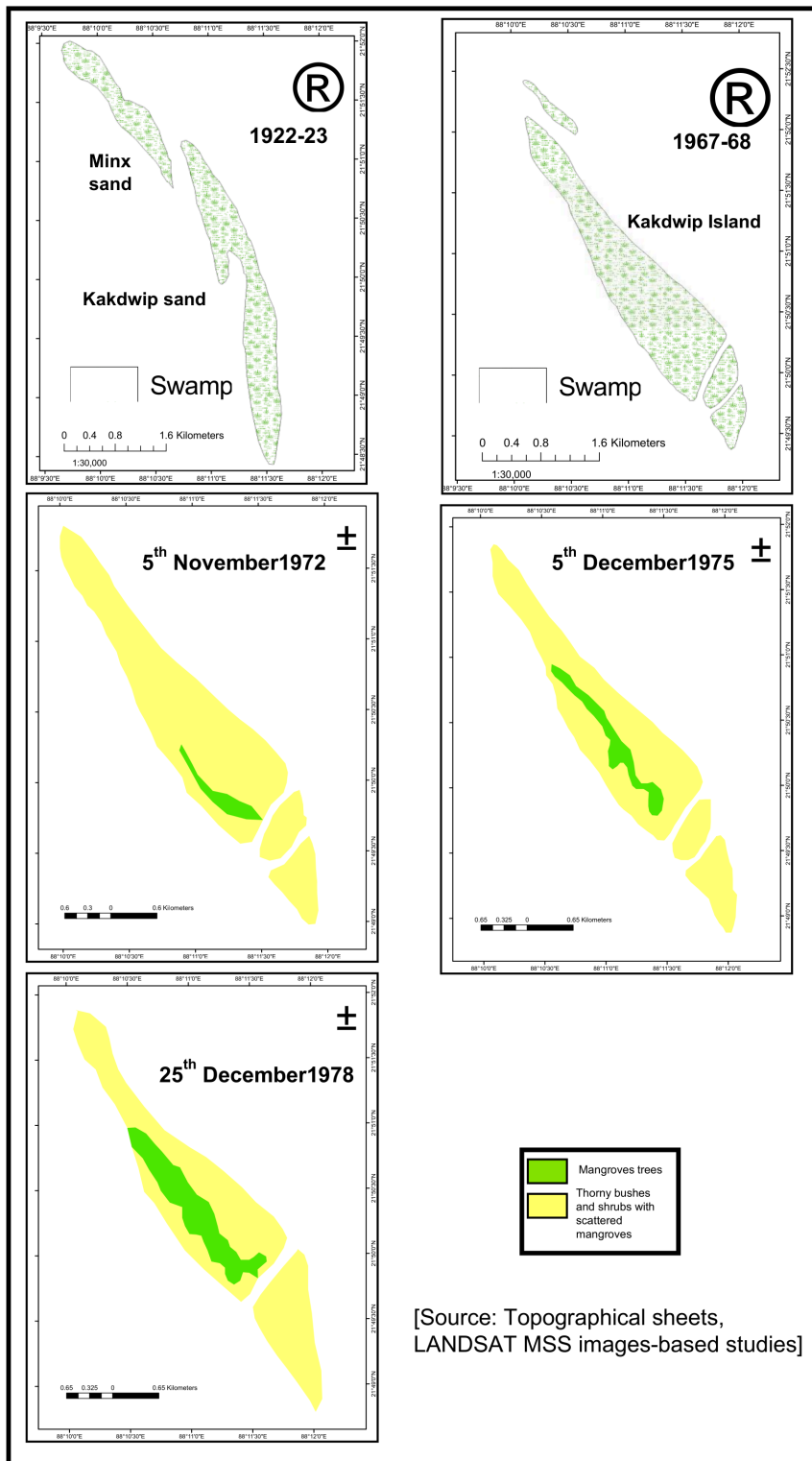


Fig. 2: The chronological distribution of mangroves from 1922-23 to 1988 shows the gradual growth of mangroves

Figure 2

See image above for figure legend

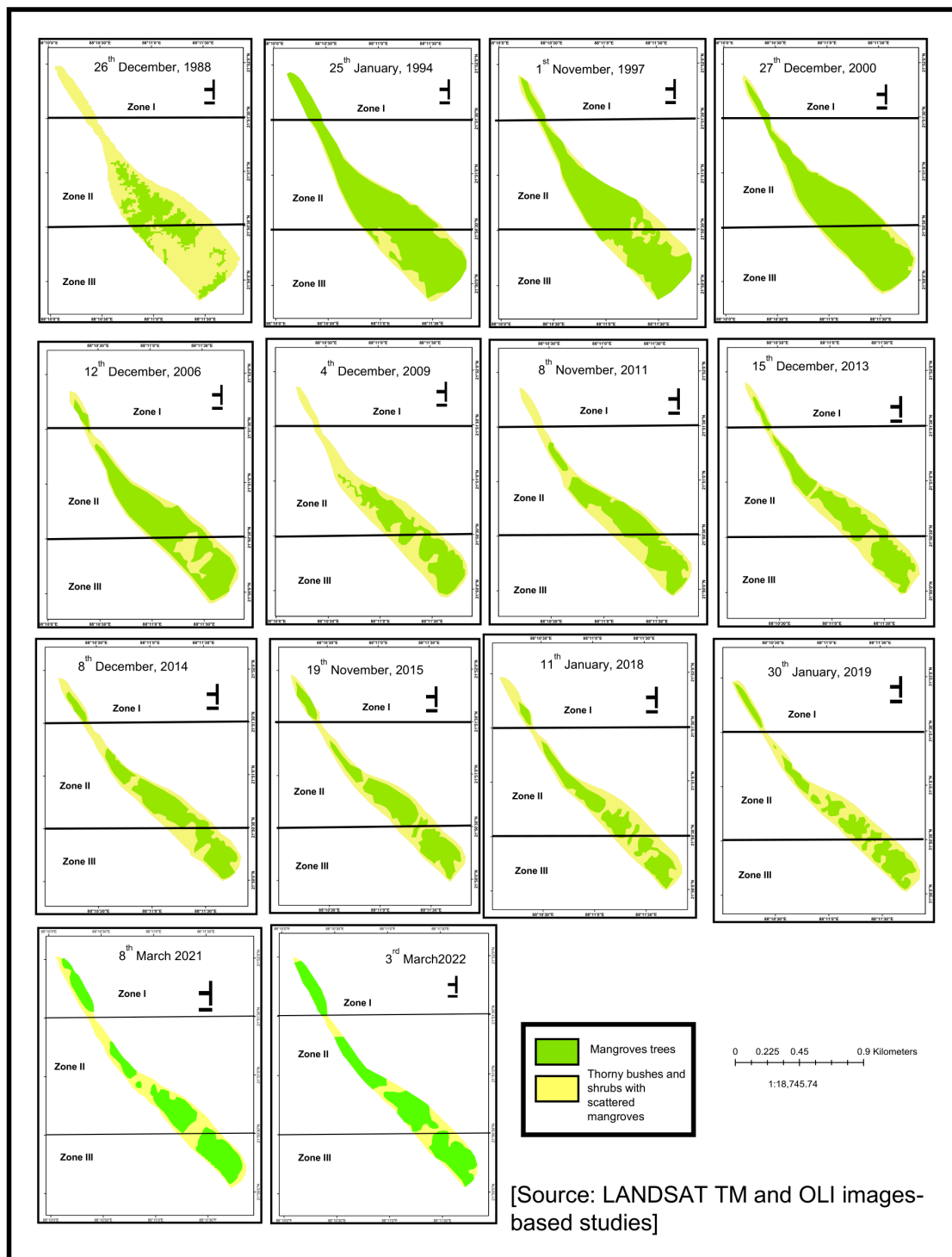


Fig. 3: The Chronological distribution of mangroves from 1988 to 2022 shows the gradual growth and decline of mangroves

Figure 3

See image above for figure legend

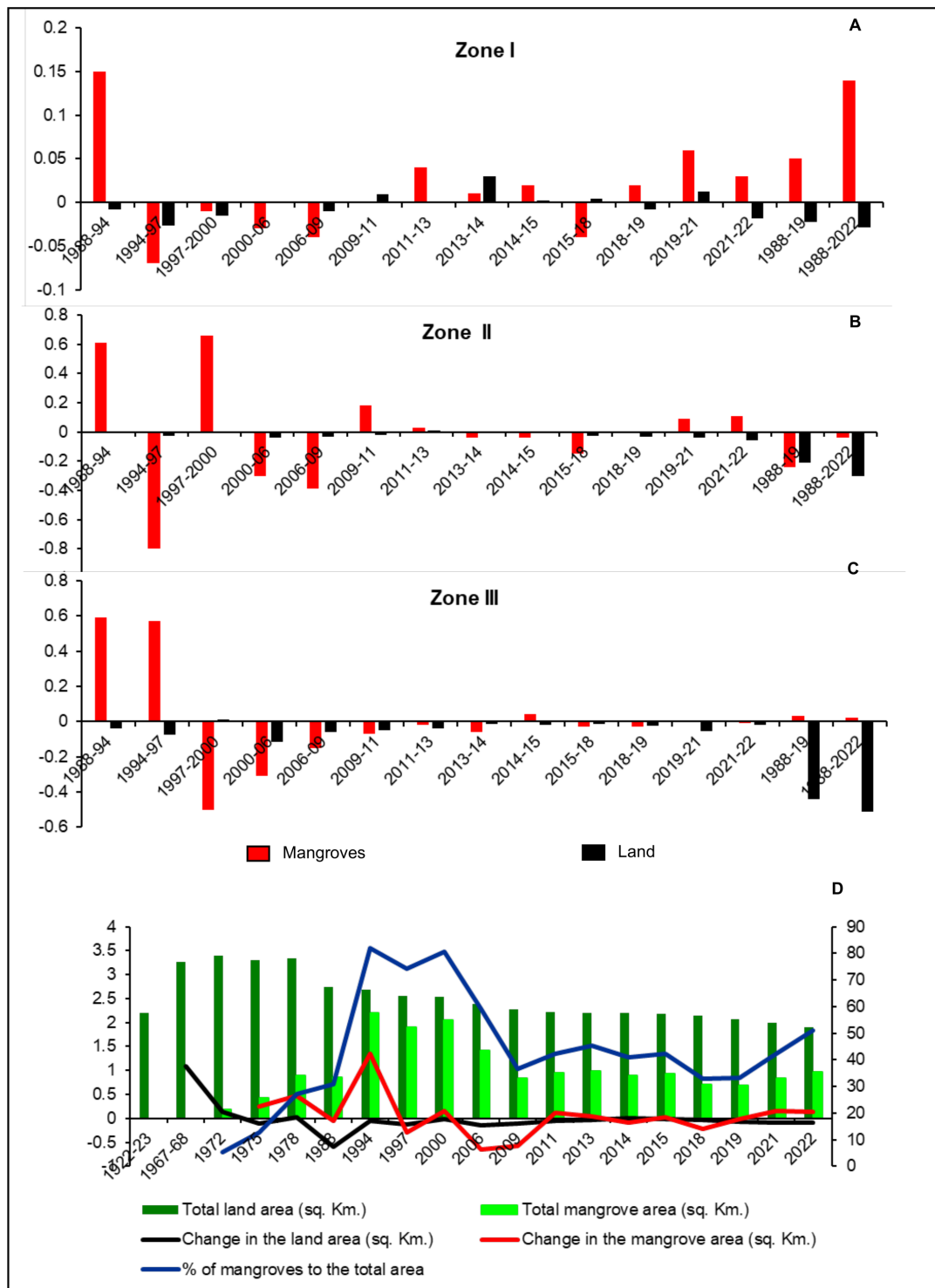


Fig. 4: Chronological change of land and mangroves (A), (B) and (C) zone-wise from 1988 to 2022, and (D) the tidal bar from 1922-23 to 2022. [Source: Remote Sensing-based analysis]

Figure 4

See image above for figure legend

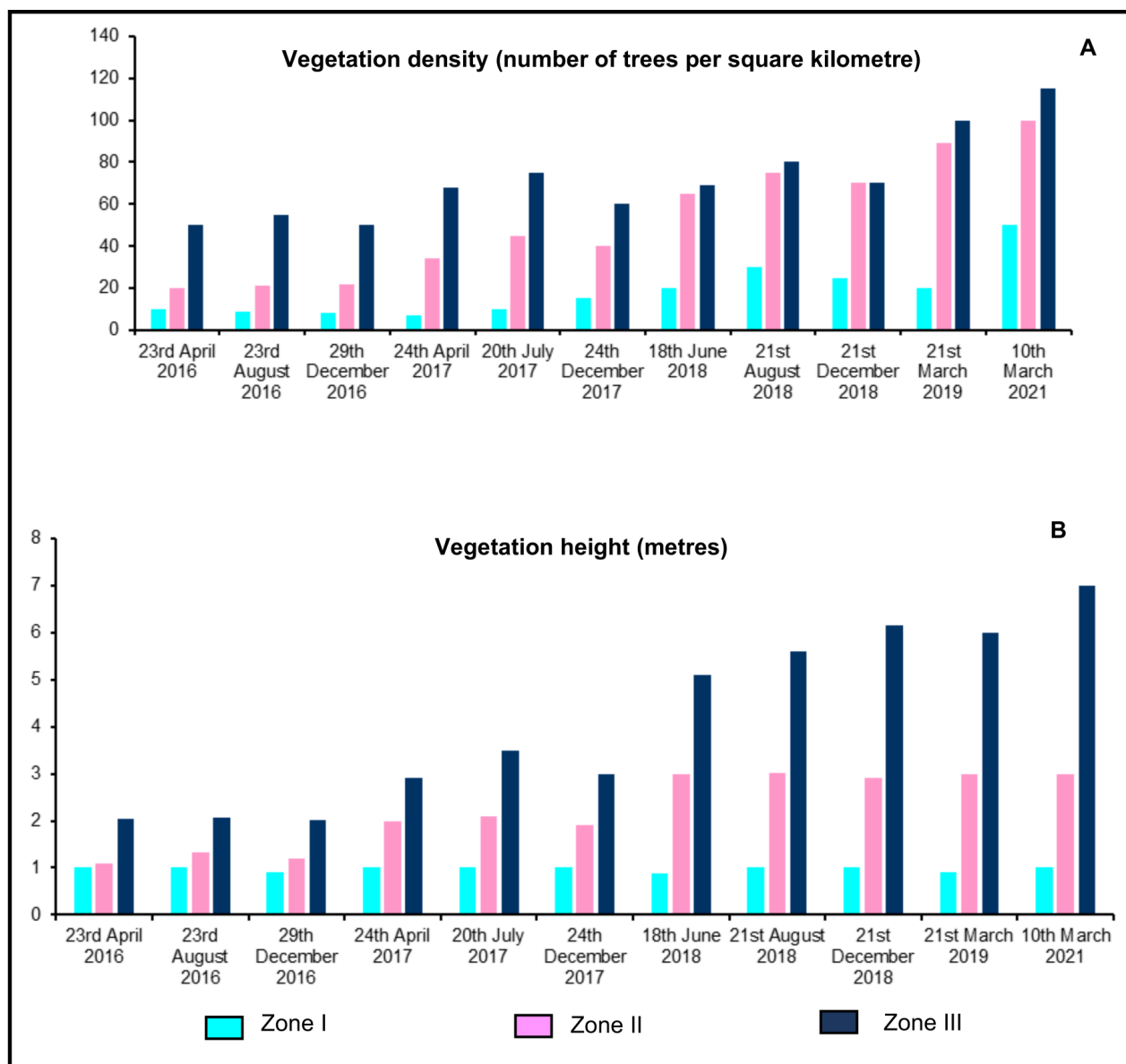


Fig. 5: Chronological change of (A) vegetation density and (B) vegetation height from 2016 to 2021. [Source: Field surveys by the research scholar]

Figure 5

See image above for figure legend

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Plate1.png](#)
- [PLate2.png](#)
- [Plate3.png](#)
- [Plate4.png](#)

- [Plate5.png](#)
- [Chart12.png](#)