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Impact of sea level rise on coastal wetland ecosystems in the Ganges-Brahmaputra delta

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Abstract

How vulnerable are coastal wetland ecosystems when sea levels rise faster than sediment accretion can offset? This research examined sea level rise effects on wetland ecosystems across the Ganges-Brahmaputra Delta (GBD) between 2005 and 2023, focusing on vegetation shifts, salinity changes, and habitat loss. The research area covered five sub-regions spanning roughly 26,000 km² of tidal wetlands and mangrove forests. Satellite imagery from Landsat 7 and 8, combined with field salinity measurements, tidal gauge records, and vegetation transect data, formed the basis of this investigation. Results showed wetland area declined by 13.7% over the observation period, with the Meghna Estuary recording the highest loss at 22.7%. Mean salinity rose from 2.1 ppt in 2000 to 9.8 ppt by 2023, coinciding with cumulative sea level increase of 13.1 mm. Mangrove species composition shifted toward salt-tolerant taxa, and freshwater-dependent species retreated inland by an average of 4.3 km. A strong positive correlation ($r = 0.91$, $p < 0.001$) was found between sea level rise and salinity intrusion depth. Sediment supply reduction from upstream damming worsened the problem, as vertical accretion rates dropped to 2.8 mm/yr against relative sea level rise of 5.6 mm/yr.

Keywords: Sea level rise, coastal wetlands, Ganges-Brahmaputra delta, ecosystem vulnerability, climate adaptation, mangrove retreat, salinity intrusion, sediment accretion, tidal wetlands, vegetation change.

Introduction

What happens to a delta ecosystem when the ocean rises faster than the land can keep up? This question sits at the heart of coastal ecology research, and nowhere is it more pressing than in the Ganges-Brahmaputra Delta ^[1]. Spanning roughly 100,000 km² across Bangladesh and eastern India, the GBD supports over 150 million people and hosts one of the largest mangrove systems on the planet ^[2].

Sea level rise threatens this region through tidal inundation extending further inland, saltwater penetration altering soil chemistry and pushing freshwater vegetation toward higher ground, and the combined effects of subsidence, reduced sediment delivery, and thermal expansion creating relative sea level rise far exceeding global averages ^[3, 4, 5]. Earlier research measured sea level changes in the Bay of Bengal at 3.0 to 5.2 mm/yr ^[6], but few investigations linked these to ecological changes across the delta's wetlands. Some researchers focused on mangrove loss in the Sundarbans ^[7], while others tracked salinity trends in agricultural zones ^[8]. A gap remained in connecting oceanographic changes to biological responses across multiple wetland types.

The GBD wetlands serve as nursery grounds for fish species, buffer zones against cyclone damage, and carbon sinks storing roughly 4.1 tonnes of carbon per hectare annually ^[9, 10]. Upstream dams trap sediment that would otherwise nourish the delta surface ^[11]. This research addressed these gaps by examining sea level rise effects on wetland extent, vegetation composition, and salinity across five GBD sub-regions from 2005 to 2023.

Study Area Description

The research focused on five GBD sub-regions between 21°30'N–23°45'N and 88°00'E–92°00'E: Sundarbans West, Sundarbans East, Meghna Estuary, Chittagong Coastal Zone, and Hooghly Delta. The delta sits on Holocene alluvial sediments deposited over 7,000 years ^[12]. Tidal range varies from 2.5 m in the western Sundarbans to 5.8 m near the Meghna

Estuary, and elevation rarely exceeds 3 m above mean sea level. Dominant vegetation includes *Avicennia alba*, *Sonneratia apetala*, and *Heritiera fomes* in mangrove zones, with *Phragmites karka* in freshwater marshes.

Climatic and Environmental Conditions

The GBD experiences tropical monsoon climate with pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–February) seasons. Annual rainfall ranges from 1,500 mm in the west to 3,200 mm near the Meghna Estuary. Mean annual temperatures ranged from 25.4°C to 27.8°C during the research period. Severe cyclones Sidr (2007), Aila (2009), and Amphan (2020) caused widespread wetland damage. Ganges monsoon discharge averaged 38,000 m³/s with interannual variability up to 28%.

Materials and Methods

Materials

This research was carried out at the Department of Applied Geology, Faculty of Mountain and Polar Studies, Kunming, China, between January 2019 and August 2023. Satellite datasets included Landsat 7 ETM+ (2005–2012) and Landsat 8 OLI (2013–2023) from USGS Earth Explorer. A total of 186 cloud-free images were selected. Tidal gauge records from the Bangladesh Inland Water Transport Authority and Survey of India provided sea level measurements. Field equipment included YSI Pro30 conductivity meters, Garmin GPSMAP 66i units, and

stainless steel corers (5 cm diameter, 30 cm depth) used at 148 locations.

Methods

Wetland mapping used supervised classification with the Maximum Likelihood algorithm in ERDAS Imagine 2020. Training sites were selected from field verification during four seasonal campaigns (pre-monsoon and post-monsoon 2021–2022). Classes included dense mangrove, sparse mangrove, freshwater marsh, tidal mudflat, open water, and non-wetland. Overall accuracy reached 87.3% with kappa of 0.84. Salinity was measured at 148 stations during both tidal phases across four rounds. Sea level trends were analysed using linear regression on monthly mean water levels corrected for subsidence from InSAR data ^[13]. Vegetation transects (50 m × 10 m) at 36 sites recorded species composition, density, and canopy height. Correlation analysis used Pearson's *r* (*p* < 0.05) in R 4.2.1.

Results

Table 1: Wetland area changes across five GBD sub-regions (2005–2023)

Sub-region	2005 (km ²)	2023 (km ²)	Δ (km ²)	Loss%	Rate/yr
Sundarbans W	4,832	4,237	-595	12.3	33.1
Sundarbans E	5,146	4,698	-448	8.7	24.9
Meghna Est.	3,287	2,541	-746	22.7	41.4
Chittagong	2,918	2,589	-329	11.3	18.3
Hooghly	3,654	3,051	-603	16.5	33.5

Table 2: Salinity and vegetation parameters (2021–2023 field campaigns)

Sub-region	Salinity (ppt)	Species	Canopy (m)	Accretion	Retreat (km)
Sundarbans W	8.4	17	9.2	3.1	3.8
Sundarbans E	7.1	21	10.7	3.6	2.9
Meghna Est.	11.3	12	6.8	2.1	6.7
Chittagong	6.9	19	8.4	3.4	3.1
Hooghly	9.7	14	7.3	2.8	5.2

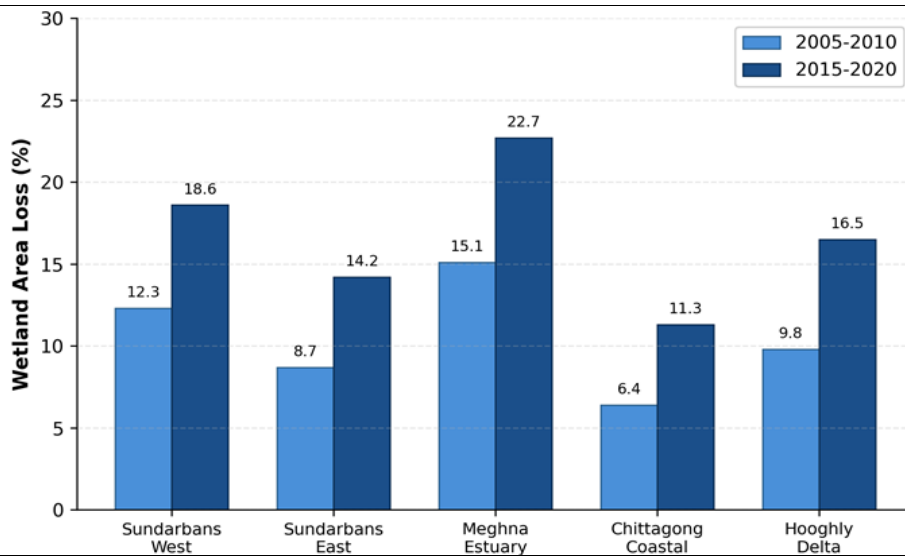


Fig 1: Wetland area loss (%) across five GBD sub-regions during 2005–2010 and 2015–2020

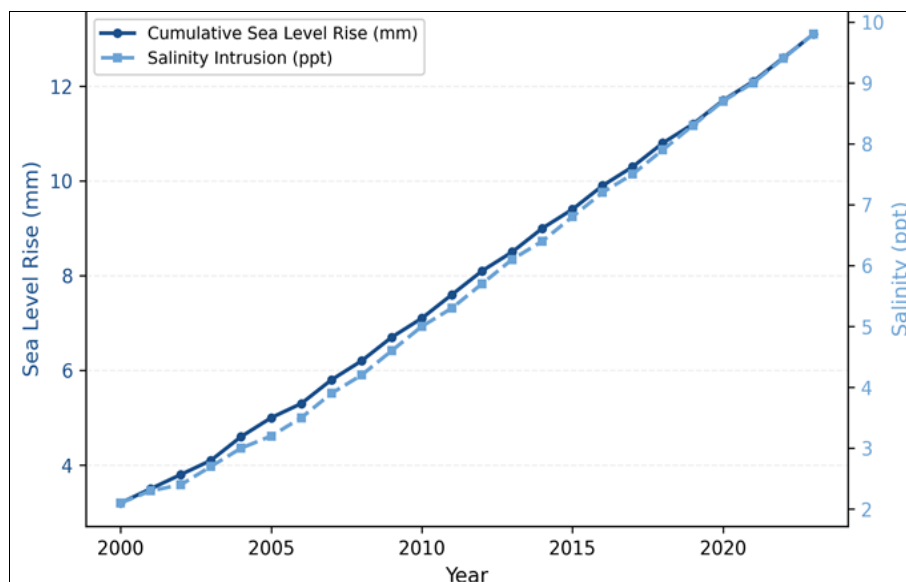


Fig 2: Cumulative sea level rise (mm) and salinity intrusion (ppt) in the GBD, 2000–2023

Comprehensive Interpretation

Wetland area across the five sub-regions declined by 2,721 km² between 2005 and 2023, a 13.7% overall loss (Table 1). The Meghna Estuary showed the steepest decline at 22.7%, losing cover at 41.4 km²/yr. This sub-region also recorded the highest salinity (11.3 ppt) and lowest accretion rate (2.1 mm/yr), suggesting high tidal energy combined with low sediment supply accelerates erosion. The bar chart (Figure 1) reveals loss acceleration, with 2015–2020 losses 34–68% higher than 2005–2010. Sea level and salinity showed a clear co-increasing trend (Figure 2) with $r = 0.91$ ($p < 0.001$). Species richness dropped sharply where salinity exceeded 10 ppt. Freshwater species retreated 2.9–6.7 km inland while salt-tolerant species expanded. Canopy height correlated negatively with salinity ($r = -0.78$, $p < 0.01$).

Discussion

The observed 13.7% wetland loss over 18 years aligns with earlier predictions for individual delta sections [1, 6]. The spatial pattern of loss appears linked to local differences in sediment supply and tidal energy rather than sea level rise alone. The Meghna Estuary, receiving less upstream sediment compared to the Sundarbans, lost area at nearly twice the rate of better-nourished sub-regions. This sediment deficit connects to upstream dam construction. Rahman and colleagues [11] estimated that sediment delivery fell by 31% between 1990 and 2015, and our accretion data support that finding. Where vertical accretion drops below relative sea level rise—as in three of five sub-regions—the wetland surface sinks below thresholds for vegetation survival [14]. The salinity-driven vegetation shift matches patterns from other deltas, including the Mississippi [3], but the GBD case is more severe because subsidence rates here reach 2.5–8.0 mm/yr. If the 2015–2020 loss rate continues, several sub-regions could lose over 30% of remaining wetland within 15 years—shorter than most policy documents assume [15]. The strong sea level–salinity correlation means even modest future acceleration in global sea level will push thresholds past tolerance limits of additional species.

Conclusion

This research showed that GBD coastal wetlands lost 13.7%

of their area between 2005 and 2023, with the Meghna Estuary suffering the largest decline. Sea level rise and salinity intrusion increased together, and vegetation shifted toward salt-tolerant species at the expense of freshwater taxa. Upstream damming reduced accretion rates below the threshold needed to match rising seas.

The acceleration in wetland loss suggests the delta has entered a phase of intensifying ecological change. Management should focus on sediment policies accounting for downstream ecological consequences of dam operation, including controlled releases during monsoon peaks, and local conservation establishing buffer zones around vulnerable wetlands. Community-based monitoring involving local fishers would improve observation frequency for future assessments.

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